U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-245 024

CONTINUOUS MEASUREMENT OF GAS COMPOSITION FROM STATIONARY SOURCES

TRW Systems Group

PREPARED FOR
Environmental Protection Agency

July 1975

KEEP UP TO DATE

Between the time you ordered this report—which is only one of the hundreds of thousands in the NTIS information collection available to you—and the time you are reading this message, several *new* reports relevant to your interests probably have entered the collection.

Subscribe to the **Weekly Government Abstracts** series that will bring you summaries of new reports *as soon as they are received by NTIS* from the originators of the research. The WGA's are an NTIS weekly newsletter service covering the most recent research findings in 25 areas of industrial, technological, and sociological interest—invaluable information for executives and professionals who must keep up to date.

The executive and professional information service provided by NTIS in the **Weekly Government Abstracts** newsletters will give you thorough and comprehensive coverage of government-conducted or sponsored research activities. And you'll get this important information within two weeks of the time it's released by originating agencies.

WGA newsletters are computer produced and electronically photocomposed to slash the time gap between the release of a report and its availability. You can learn about technical innovations immediately—and use them in the most meaningful and productive ways possible for your organization. Please request NTIS-PR-205/PCW for more information.

The weekly newsletter series will keep you current. But *learn what you have missed in the past* by ordering a computer **NTISearch** of all the research reports in your area of interest, dating as far back as 1964, if you wish. Please request NTIS-PR-186/PCN for more information.

WRITE: Managing Editor
5285 Port Royal Road
Springfield, VA 22161

Keep Up To Date With SRIM

SRIM (Selected Research in Microfiche) provides you with regular, automatic distribution of the complete texts of NTIS research reports *only* in the subject areas you select. SRIM covers almost all Government research reports by subject area and/or the originating Federal or local government agency. You may subscribe by any category or subcategory of our WGA **(Weekly Government Abstracts)** or **Government Reports Announcements and Index** categories, or to the reports issued by a particular agency such as the Department of Defense, Federal Energy Administration, or Environmental Protection Agency. Other options that will give you greater selectivity are available on request.

The cost of SRIM service is only 45¢ domestic (60¢ foreign) for each complete microfiched report. Your SRIM service begins as soon as your order is received and processed and you will receive biweekly shipments thereafter. If you wish, your service will be backdated to furnish you microfiche of reports issued earlier.

Because of contractual arrangements with several Special Technology Groups, not all NTIS reports are distributed in the SRIM program. You will receive a notice in your microfiche shipments identifying the exceptionally priced reports not available through SRIM.

A deposit account with NTIS is required before this service can be initiated. If you have specific questions concerning this service, please call (703) 451-1558, or write NTIS, attention SRIM Product Manager.

This information product distributed by

NTIS U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161

268278

PB 245 024

EPA-600/2-75/012

July 1975

Environmental Protection Technology Series

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
US Department of Commerce
Springfield, VA. 22151

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-75-012	2.
3. RECIPIENT'S ACCESSION NO.	
4. TITLE AND SUBTITLE Continuous Measurement of Gas Composition from Stationary Sources	5. REPORT DATE July 1975 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) E. F. Brooks, C. A. Flegal, L. N. Harnett, M. A. Kolpin, D. J. Luciani, and R. L. Williams	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS TRW Systems Group One Space Park Redondo Beach, CA 90278	10. PROGRAM ELEMENT NO. 1AB013; ROAP 21ACX-132 11. CONTRACT/GRANT NO. 68-02-0636
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED Final; 7/74 - 3/75 14. SPONSORING AGENCY CODE
15. SUPPLEMENTARY NOTES	

16. ABSTRACT

The program objective was to develop and evaluate methods for the continuous measurement of gaseous emissions from stationary sources, specifically in large or complex ducts where total flow processing techniques are not practical. This report is concerned with the measurement of mean gas concentrations in rectangular ducts. Work consisted of a review of related programs, development of a computer program to assess stratification levels and evaluate sampling techniques, formulation and evaluation of point sampling methods for continuous monitoring, development of a multi-port continuous gas sampling probe, and field demonstration of hardware and techniques. Results showed that emissions can be accurately monitored using as few as one flow sensor and one sampling probe, even in the presence of significant velocity and compositional stratification, although stratification levels were too high for single point samples to be acceptable. It was shown for all data examined that good accuracy can be attained by taking a spatial concentration average -- flow proportional sampling is not required. The field demonstration verified the acceptability of the proposed methodology.

PRICES SUBJECT TO CHANGE

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution Flue Gases Chemical Analysis Continuous Sampling Measurement Stratification	Air Pollution Control Stationary Sources	13B 21B 07D 14B

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS *(This Report)* Unclassified 20. SECURITY CLASS *(This page)* Unclassified	21. NO. OF PAGES 125 22. PRICE

EPA Form 2220-1 (9-73)

EPA-600/2-75/012

CONTINUOUS MEASUREMENT OF GAS COMPOSITION FROM STATIONARY SOURCES

by

E. F. Brooks, C. A. Flegal, L. N. Harnett,
M. A. Kolpin, D. J. Luciani, and R. L. Williams

TRW Systems Group
One Space Park
Redondo Beach, California 90278

Contract No. 68-02-0636
ROAP No. 21ACX-132
Program Element No. 1AB013

EPA Project Officer: William B. Kuykendal

Industrial Environmental Research Laboratory
Office of Energy, Minerals, and Industry
Research Triangle Park, North Carolina 27711

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF RESEARCH AND DEVELOPMENT
WASHINGTON, D.C. 20460

July 1975

EPA REVIEW NOTICE

This report has been reviewed by the National Environmental Research Center - Research Triangle Park, Office of Research and Development, EPA, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

RESEARCH REPORTING SERIES

Research reports of the Office of Research and Development, U.S. Environmental Protection Agency, have been grouped into series. These broad categories were established to facilitate further development and application of environmental technology. Elimination of traditional grouping was consciously planned to foster technology transfer and maximum interface in related fields. These series are:

1. ENVIRONMENTAL HEALTH EFFECTS RESEARCH
2. ENVIRONMENTAL PROTECTION TECHNOLOGY
3. ECOLOGICAL RESEARCH
4. ENVIRONMENTAL MONITORING
5. SOCIOECONOMIC ENVIRONMENTAL STUDIES
6. SCIENTIFIC AND TECHNICAL ASSESSMENT REPORTS
9. MISCELLANEOUS

This report has been assigned to the ENVIRONMENTAL PROTECTION TECHNOLOGY series. This series describes research performed to develop and demonstrate instrumentation, equipment and methodology to repair or prevent environmental degradation from point and non-point sources of pollution. This work provides the new or improved technology required for the control and treatment of pollution sources to meet environmental quality standards.

This document is available to the public for sale through the National Technical Information Service, Springfield, Virginia 22161.

Publication No. EPA-600/2-75-012

ABSTRACT

The program objective was to develop and evaluate methods for the continuous measurement of gaseous emissions from stationary sources, specifically in large or complex ducts where total flow processing techniques are not practical. This report is concerned with the measurement of mean gas concentrations in rectangular ducts. Work consisted of a review of related programs, development of a computer program to assess stratification levels and evaluate sampling techniques, formulation and evaluation of point sampling methods for continuous monitoring, development of a multi-port continuous gas sampling probe, and field demonstration of hardware and techniques. Results showed that emissions can be accurately monitored using as few as one flow sensor and one sampling probe, even in the presence of significant velocity and compositional stratification, although stratification levels were too high for single point samples to be acceptable. It was shown for all data examined that good accuracy can be attained by taking a spatial concentration average -- flow proportional sampling is not required. The field demonstration verified the acceptability of the proposed methodology.

This report was submitted in fulfillment of Contract No. 68-02-0636, by TRW Systems Group under the sponsorship of the Industrial and Environmental Research Laboratory-RTP, of the Environmental Protection Agency. Work was completed as of March 1975.

CONTENTS

		Page
Abstract		iii
List of Figures		vi
List of Tables		ix
Acknowledgements		x
Sections		
I	Conclusions	1
II	Recommendations	2
III	Introduction	3
IV	Task I - Data Review	5
	4.1 Review of Stratified Gas Program Results	5
	4.2 Analytical Considerations	7
	4.3 Desired System Accuracy	17
V	Task II - Flow Analysis Program	20
	5.1 Program Development	20
	5.2 Program Description	21
	5.3 Typical Program Results	23
VI	Task III - Mapping Technique Evaluation	27
	6.1 Exxon Data	27
	6.2 TVA Data	43
	6.3 Preliminary Sampling Technique Conclusions	50
VII	Task IV - Sample Probe Development	51
	7.1 Prototype Probe Design	51
	7.2 Suggestions for Improved Probe Design	51

CONTENTS (Cont'd)

		Page
VIII	Task V - Field Demonstrations	57
	8.1 Facility Description	57
	8.2 Test Conduct	60
	8.3 Flow Data Correlation	66
	8.4 Test Results	66
	8.5 Summary of Results	92
IX	Discussion of Results	95
X	References	99
XI	Glossary	100
XII	Appendix	101

FIGURES

No.		Page
1.	Flow Measurement Control Volume	8
2.	Duct Analogy for Transformation of Test Velocity to Standard Velocity	11
3.	Histogram of Deviations from Mean Value for NO_x Traverse	16
4.	Row Average Analysis for CO_2 Concentration Map -- Exxon Run 1	25
5.	Normalized CO_2 Concentration Distribution -- Exxon Run 1	26
6.	Location of Sampling Plane for Exxon data -- TVA Widows Creek Unit 7	28
7.	Duct Shapes for Exxon and TVA Tests	29
8.	Normalized CO_2 Concentration Distribution -- Exxon Run 1	30
9.	Normalized CO_2 Concentration Distribution -- Exxon Run 2	31
10.	Normalized SO_2 Concentration Distribution -- Exxon Run 1	32
11.	Normalized SO_2 Concentration Distribution -- Exxon Run 2	33
12.	Normalized NO Concentration Distribution -- Exxon Run 1	34
13.	Normalized NO Concentration Distribution -- Exxon Run 2	35
14.	Normalized O_2 Concentration Distribution -- Exxon Run 1	36
15.	Normalized O_2 Concentration Distribution -- Exxon Run 2	37
16.	Row Average Analysis for Gas Concentration Maps -- Exxon Runs 1 and 2	42

FIGURES (Cont'd.)

No.		Page
17.	Normalized SO_2 Concentration Distribution -- TVA Run 1	44
18.	Normalized SO_2 Concentration Distribution -- TVA Run 2	45
19.	Normalized SO_2 Concentration Distribution -- TVA Run 3	46
20.	Normalized SO_2 Concentration Distribution -- TVA Run 4	47
21.	Row Average Analysis for SO_2 Concentration Maps -- TVA Runs 1-4	49
22.	Multi-Port Sampling Probe Basic Design	52
23.	Suggestions for Continuous Gas Sample Probe Modifications to Prevent Particulate Entry Into the Probe	55
24.	Schematic of Moapa Power Plant	58
25.	Duct 1 Geometry	59
26.	Point Sampling Probe	61
27.	Multi-Hole Sampling Probe for Field Demonstration	63
28.	Schematic of Gas Sampling Train for Field Demonstration	64
29.	Normalized CO_2 Concentration Distribution - Duct 1, 1974	73
30.	Normalized O_2 Concentration Distribution - Duct 1, 1974	74
31.	Normalized NO_x Concentration Distribution - Duct 1, 1974, Run 1	75
32.	Normalized NO_x Concentration Distribution - Duct 1, 1974, Run 2	76
33.	Normalized CO_2 Concentration Distribution - Duct 1, 1975	77
34.	Normalized O_2 Concentration Distribution - Duct 1, 1975	78
35.	Normalized SO_2 Concentration Distribution - Duct 1, 1975	79
36.	Normalized NO_x Concentration Distribution - Duct 1, 1975, Run 1	80
37.	Normalized NO_x Concentration Distribution - Duct 1, 1975, Run 2	81
38.	Normalized CO_2 Concentration Distribution - Duct 2, 1975	82

FIGURES (Cont'd.)

No.		Page
39.	Normalized O_2 Concentration Distribution - Duct 2, 1975	83
40.	Normalized SO_2 Concentration Distribution - Duct 2, 1975	84
41.	Normalized NO_x Concentration Distribution - Duct 2, 1975, Run 1	85
42.	Normalized NO_x Concentration Distribution - Duct 2, 1975, Run 2	86
43.	Row Average Analysis for CO_2, O_2, and SO_2 Concentration Maps -- Field Demonstration, Duct 1	87
44.	Row Average Analysis for NO_x Concentration Maps -- Field Demonstrations, Duct 1	88
45.	Row Average Analysis for CO_2, O_2, SO_2, and NO_x Concentration Maps -- Field Demonstrations, Duct 2	89

TABLES

No.		Page
1.	Comparison of Deviations for Actual and Normal Distributions	15
2.	Typical Analysis Program Results	24
3.	Mean Values and Stratification Levels for Exxon Data	39
4.	CO_2 Tracer Method Analysis of Exxon Data	41
5.	Mean Values and Stratification Levels for TVA SO_2 Concentration Data	48
6.	Mean Values and Stratification Levels for 1974 Field Demonstration	67
7.	Mean Values and Stratification Levels for 1975 Field Demonstration	69
8.	Computation of Total Flow from Coal Analysis and Measured CO_2 Concentration, 1974	70
9.	Average Daily Flow Through Ducts, 1975	71
10.	Multi-Hole Sampling Probe Overnight Sampling Results, 1975	90
11.	CO_2 Tracer Method Analysis of Field Demonstration Data	91
12.	Short Term Stationary Point Gas Sample Data, 1974, Duct 1	93
13.	Overnight NO_x Gas Sample Data, 1974	94

ACKNOWLEDGEMENTS

Program personnel are grateful to the Nevada Power Company for their assistance and use of facilities for the field demonstrations. We also wish to thank Exxon Research and Engineering Company for use of their data obtained during EPA contract 68-02-1722, "Determination of the Magnitude of SO_2, NO, CO_2, and O_2 Stratification in the Ducting of Fossil Fuel Fired Power Boilers," and the Thermo Electron Corporation for the loan of an SO_2 analyzer during the second field demonstration.

SECTION I
CONCLUSIONS

- Single point gas sampling is considered unacceptable from an accuracy standpoint due to the high stratification levels and poor temporal repeatability of the cases examined.
- For gas sample traverses, spatial concentration averages are as accurate as flow proportional concentration averages in rectangular ducts for most engineering purposes. This justifies the development of continuous sampling systems which do not need to take local flow velocity into account.
- Measurement techniques developed during the program can be used to reliably measure total mass flow, gas species concentration, and gas species mass emission to accuracies of 5-10 percent, 2-6 percent, and 11-14 percent, respectively, in rectangular ducts on a continuous basis. This can be accomplished through the use of as few as one flow sensor and one sampling probe.
- The row average technique, developed originally for velocity measurement during the first phase of the program, is also acceptable for continuous gas sampling. Rows should be taken in the direction of maximum compositional stratification whenever possible.
- The stratification level of gases for the data examined varied from 8 percent to about 40 percent of the mean concentration value, and was generally in the 10-20 percent range.
- Poor correlation was observed for the CO_2 Tracer Method.
- Use of continuous gas analyzers is much more compatible with spatial gas sampling than with flow proportional sampling.

SECTION II
RECOMMENDATIONS

- The data base for comparison of spatial and flow proportional averages should be expanded to fully verify the adequacy of spatial sampling.
- Applicability of developed methods to sampling in circular ducts needs to be assessed.
- Development of multi-point continuous gas sampling probes should be pursued.
- Agreement between results of traverses involving as few as 24 sampling points and the expanded computer matrix of 525 points suggests that work should be done to determine a reasonable maximum number of sample points for traverses. Reducing the number of points would also reduce errors due to temporal variation during the traverse.
- Extensive work should be performed at a representative site, such as an EPA demonstration plant, to fully assess the extent of temporal concentration variations in a process stream and their effect on the accuracy of both manual traverses and continuous measurements.
- A standard quantitative definition of the term "stratification level" needs to be adopted. It is recommended that the 2σ designation used in the program be adopted for this purpose, where 2σ is twice the standard deviation of traverse points from the mean concentration.

SECTION III
INTRODUCTION

The objective of the program is to develop methods to measure total gaseous mass emissions and individual gas species emissions from stationary sources on a continuous basis. Continuous monitoring is important for both process control and compliance with emission standards. The primary methodological difficulty involved in continuous monitoring is due to stratification of both velocity and composition in the stream. The sampling methods developed during the program apply in general to any stationary source.

The program is concerned with point sampling methods in large ducts, that is ones where monitoring of the total flow is impractical. The first phase of the program was concerned with the measurement of total mass emission (total volumetric flow rate) in rectangular and circular ducts, and a report (Reference 1) has been issued documenting the results. This report is concerned with measurement of gas concentrations, which are coupled with flow data to determine constituent gaseous emissions. Work during this part of the program was concerned with measurements in rectangular ducts only due to shortage of data for circular ducts. It is felt that measurements in rectangular ducts represent the more difficult problem, and that the methods developed for that case can be easily adapted to circular ducts. Examination of existing data showed single point monitoring to be unacceptable. It was also recognized that continuous monitoring systems using a large number of sampling points would be too expensive and complex. The general approach used was to consider methods which extract samples from a number of discrete points in the process stream, then mix and analyze the samples. Emphasis was placed on minimizing the number of sampling points and specifying optimum locations.

The program began in October 1972. The gas sampling phase started in July 1974, and the technical effort was concluded in March 1975. The task breakdown was as follows:

Task I Data Review. The effort was begun with a review of an EPA program on stratified gas measurement conducted by Walden Research. Baseline work was then performed to determine a viable method for specification of stratification levels, and to determine desired system accuracies.

Task II Flow Analysis Program. A computer program was developed to evaluate stratification data and determine the applicability of proposed sampling techniques.

Task III Mapping Technique Evaluation. The analysis program developed in Task II was used to analyze sample traverse data obtained from the Walden Research report and from a stratification assessment program conducted by Exxon Research and Engineering Company. Results were used to select methods for field evaluation in Task V.

Task IV Sample Probe Development. A multi-port sampling probe was designed and prototype units were fabricated for field evaluation. The probe was designed to obtain samples for the Row Average sampling method, which was initially developed and successfully demonstrated for velocity measurement.

Task V Field Demonstrations. Assessment of stratification levels and demonstration of continuous sampling techniques were performed during two field demonstrations at the Nevada Power Company station at Moapa, Nevada.

The most important program results were the discovery that the average stratification level was on the order of 10-15%, which resulted in the conclusion that single point sampling is not generally acceptable, and the discovery that spatial average concentrations agreed with flow proportional average concentrations to within an average of 2% for all data considered in spite of the stratification levels. The latter result means that concentration and flow data can be taken independently and still be used to accurately determine species mass emissions. This greatly simplifies hardware for continuous monitoring systems. As a result of this discovery, emphasis was placed on development of spatial averaging techniques. A monitoring system employing a single flow probe and a single sampling probe showed accuracies on the order of 2-3% for total and constituent mass emissions during the second field demonstration.

SECTION IV
TASK I - DATA REVIEW

The objective of this phase of the program was to determine suitable methods for continuous gas sampling, and to combine these methods with those developed under the first phase of the program for measurement of total volumetric flow. At the time Phase II of this program started, EPA program 68-02-1306, "Procedure for Measurement in Stratified Gases," performed by Walden Research Division of Abcor, Inc., had recently been completed. By design, the results of the Walden program served as the basis for Phase II gas sampling work. The first task was begun with analysis of the Walden report (Ref. 2, EPA Report EPA-650/2-74-086-a) and a review in their facility. This was followed by a survey of requirements and analytical techniques used in gas sampling. Results were used to determine the type and extent of work required for subsequent Phase II tasks.

4.1 REVIEW OF STRATIFIED GAS PROGRAM RESULTS

The following excerpts are from pages 1 and 2 of Reference 2:

CONCLUSIONS

> Results from the literature and field surveys indicate that gas stratification exists, but it is likely to be less general and less severe than particulate stratification. For a given gas stream, it is necessary to make a preliminary gas concentration survey to determine the existance of spatial stratification.
>
> Where stratification exists, we have concluded as a result of this program, that there are two methods of obtaining representative gas samples. Where conditions permit, we recommend a system of monitoring the ratio of pollutants such as SO_2, NO_x, etc. to CO_2 from a single location. Then from the measured fuel flow and

chemistry of the process, the mass flow of CO_2 is the mass flow of the pollutant. Where conditions do not permit such a system, we recommend a schedule of manual surveys and installation of a multi-element proportional sampler and gas velocity array.

RECOMMENDATIONS

In the course of this project, areas requiring further development were identified. These are as follows:

A. A program is needed to develop an automatic instrumentation system for extracting continuous representative gas samples from stratified gas streams, for example, a multi-probe automatic proportional gas sampler which would be practical in terms of cost and adaptability to various process streams.

B. A program is needed to develop techniques for determining the total gas flow profile or velocity vector in process streams. It is likely that in practice a significant fraction of errors in emission measurements are attributable to errors in gas velocity/flow determination.

C. Further documentation of the extent and frequency of gas stratification in process streams together with statistical analyses of data would be helpful in refining sampling methodologies.

The first conclusion and third recommendation were given first consideration. It is clear that the extent of stratification present in a process stream is a major factor in determining required gas sampling techniques. In their field work, Walden found no evidence of significant gas stratification in tests in oil-fired power plants in Weynouth, Massachusetts and Boston (Boston Edison Mystic Station) or in a coal-fired power plant in Bow, New Hampshire. Typical maximum deviations from the mean concentration for CO_2 and SO_2 were $\pm 15\%$, with average deviations from the mean on the order of $\pm 4\%$.

For a continuous monitoring system, it would seem reasonable that the number of sampling points required would increase with increasing compositional stratification. Hardware cost would in turn be proportional to the number of sampling points, which is clearly not the case for manual sampling. Assessment of stratification levels to be expected under normal circumstances is then very important in terms of eventual hardware costs and system complexity.

The review of the Walden report made it clear that the following work would need to be performed:

- Develop analysis techniques to determine stratification levels in a simple, uniform manner.
- Expand the data base for compositional stratification to determine the severity of the problem.
- Develop a methodology for continuous gas sampling and/or verify the acceptability of the Walden CO_2 tracer method.

4.2 ANALYTICAL CONSIDERATIONS

4.2.1 Proportional Sampling Requirements

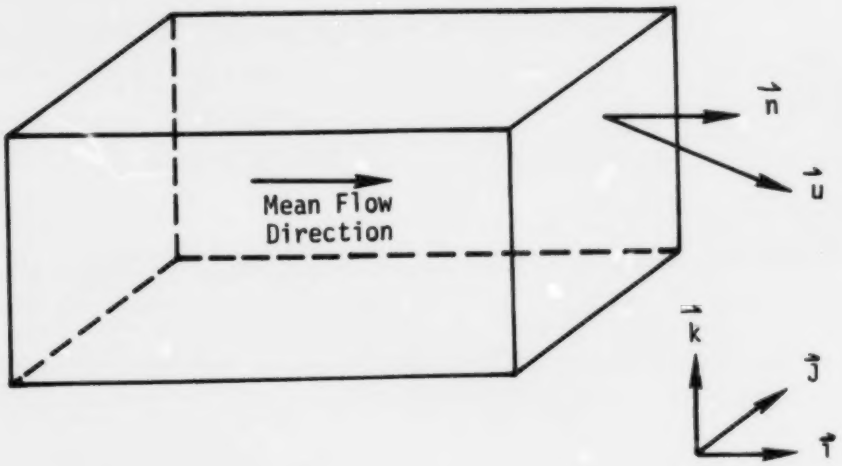
The first step in formulating the required analytical techniques is to start with the basic flow equations. Consider the duct shown in Figure 1. The four sides and the entry and exit planes form a control volume. By definition, the sides are solid, so that all fluid must enter through the left plane and leave through the right plane. For simplicity (which does not compromise accuracy), assume that the flow rate into the control volume is always exactly the same as the flow rate out of the control volume. This relation becomes true as the size of the control volume approaches zero. The flow through the control volume may then be given as the flow through the exit plane of the control volume:

$$\dot{m} = \iint_A \rho \vec{u} \cdot \vec{n} \, dA = \overline{\rho u} \, A \qquad (1)$$

where

$\dot{m}$ = mass flow rate, gm/sec

ρ = local fluid density, gm/cm^3 (gas phase only)



Flow enters from the left and exits to the right.

Velocity at a point in the exit plane is given by

$$\vec{u} = u\vec{i} + v\vec{j} + w\vec{k}$$

where

$\vec{i}$, $\vec{j}$, $\vec{k}$ are unit vectors in the directions shown, forming an orthogonal coordinate system

and

u, v, w are the scalar components of $\vec{u}$ in the $\vec{i}$, $\vec{j}$ and $\vec{k}$ directions, respectively

The vector $\vec{n}$ is the unit vector normal to the exit plane, so that

$$\vec{n} \equiv \vec{i}$$

and the net flow component out of the duct at the point shown is

$$\vec{u} \cdot \vec{n} = u$$

Figure 1. Flow measurement control volume

$\vec{u}$ = local velocity (vector), m/sec

$\vec{n}$ = unit vector normal to exit plane, dimensionless

A = exit plane area, m^2

$u = \vec{u} \cdot \vec{n}$, scalar velocity component normal to exit plane, m/sec

This equation represents the total instantaneous gas flow through the control volume. In gas sampling work, it is desirable to know the instantaneous mass flow of a specific constituent, such as O_2 or SO_2, for control and/or regulatory purposes. For this case, we have

$$\dot{m}_i = \iint \rho i \, \vec{u} \cdot \vec{n} \, dA \qquad (2)$$

where

$( )_i$ denotes the property relative to species i, e.g.

$\dot{m}_i$ = mass flow of species i, gm/sec

ρi = mass density of species i, gm/cm^3

This can be put in terms of normally measured parameters as follows:

$$\rho_i = c_i M_i = c \mu_i M_i \qquad (3)$$

where

c = global concentration, $moles/cm^3$

c_i = concentration of species i, moles of i/cm^3

M_i = molecular weight of species i, grams of i/mole of i

μ_i = mole fraction of species i, moles of i/mole

$$c = \frac{RT}{p} \qquad (4)$$

where

R = universal gas constant, $\frac{gm \cdot m^2}{mole \cdot sec^2 \cdot °K}$

T = absolute temperature, °K

p = absolute pressure, torr

Substituting in equation (2), we get

$$\dot{m}_i = \iint \frac{RT}{p} \mu_i M_i \vec{u} \cdot \vec{n} \, dA \tag{5}$$

or

$$\dot{m}_i = R M_i A \frac{\overline{T \mu_i u}}{p} \tag{6}$$

where the average is defined by correct evaluation of the integral in equation (5). Equation (6) is now in terms of the basic engineering parameters commonly measured in a gas flow. The mole fraction μ_i is commonly given in units of parts per million for gases such as SO_x and NO_x, and in mole percent for N_2, O_2, H_2O, and CO_2.

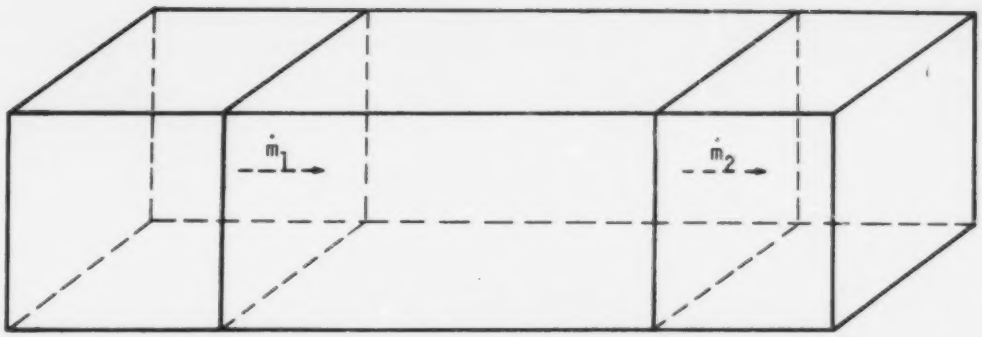
It is common practice to evaluate equation (5) by means of a gas sample traverse. The integration is then approximated by the summation

$$\dot{m}_i \doteq R M_i \sum_{n=1}^{N} \frac{T_n}{p_n} (\mu_i)_n \, u_n \Delta A_n \tag{7}$$

for N area segments. Usually the segments are of equal area, so that

$$\dot{m}_i \doteq \frac{A}{N} R M_i \sum_{n=1}^{N} \frac{T_n}{p_n} (\mu_i)_n u_n \tag{8}$$

This is the practical form of equation (5). It shows that for accurate gas sampling measurements, the local velocity component normal to the sampling plane and the local static pressure and temperature must be measured as well as the local concentration (Note: from this point on, the term μ_i will be referred to as "concentration" rather than "mole fraction" in accordance with common practice). Temperature and pressure effects are most easily handled through introduction of the concept of "velocity at standard conditions." This is illustrated in Figure 2. For this control volume, the gas enters at arbitrary pressure and temperature. It then undergoes whatever changes are required in order to emerge uniformly with a static temperature of 20°C and at an absolute static pressure of 760 torr, which have been defined as standard conditions for this program. Also by definition, the gas is considered to be chemically frozen and there are no phase changes. This is important from a practical measurement standpoint. It means that the mass flow rate being considered is that of



	STATION 1 (TEST)	STATION 2 (STANDARD)
TEMPERATURE	T_1	T_s
PRESSURE	p_1	p_s
DENSITY	ρ_1	ρ_s
VELOCITY	$\mathcal{V}_1$	$\mathcal{V}_s$
AREA	A	A

FROM CONSERVATION OF MASS,

$$\dot{m}_1 = \dot{m}_2$$

SO

$$\rho_1 \mathcal{V}_1 A = \rho_s \mathcal{V}_s A$$

AND

$$\mathcal{V}_s = \frac{\rho_1}{\rho_s} \mathcal{V}_1$$

Figure 2. Duct analogy for transformation of test velocity to standard velocity

the gaseous components only, since common velocity sensors for operation in a gas stream respond to gas flow, and not to liquids or solids which may be entrained in the flow. Therefore defining a gas flow in terms of standard rather than actual conditions implies changes in pressure and temperature only -- not composition and phase. Thus for any one area segment where the velocity and density are considered to be uniform,

$$\frac{T}{p} u = \frac{T_s}{p_s} u_s \tag{9}$$

where

$( )_s$ = value at standard atmospheric conditions

so that

$$\dot{m}_i = \frac{AT_s}{Np_s} RM_i \sum_{n=1}^{N} (\mu_i)_n (u_s)_n \tag{10}$$

or

$$\dot{m}_i = \frac{AT_s}{Np_s} RM_i \overline{\mu_i u_s} \tag{11}$$

Thus for the term "proportional sampling" to be truly correct, it should be interpreted as "sampling in proportion to the local velocity at standard conditions" so that temperature and pressure effects are not ignored.

The proportional gas sampling requirement inherent in equation (11) is the source of significant practical difficulties in the field, since the sampling rate must be changed for each point when standard wet chemistry methods are used. Common use of continuous gas analyzers may be expected to change this approach. For that technique, it is easier to monitor the local value of μ_i with the analyzer, then multiply by the local velocity to obtain the local mass flow rate. This was the approach taken for all field work during the program, and is also the approach one would expect to take in designing a continuous multi-point sampling system. The alternative is somewhat less attractice -- it would require obtaining a volume of sample from each point, where the volume is proportional to the local velocity. These samples would then have to be mixed thoroughly in some type of mixing chamber and delivered to the analyzer. It is felt

that the hardware requirements for this approach would be more expensive and difficult to maintain than the software requirements for the first method.

There is a third alternative which became apparent as a result of the fairly low stratification levels reported by Walden: simple spatial sampling rather than proportional sampling. Proportional sampling is represented by the term $\overline{\mu_i u_s}$ in equation (11), which denotes that the true constituent mass flow rate is given by the average of the products of local concentration and local velocity. This is mathematically different from the product of the average concentration and the average velocity, i.e. in general,

$$\mu_i u_s \neq \overline{\mu_i} \cdot \overline{u_s} \tag{12}$$

The only times actual equivalence is guaranteed is if either concentration or velocity is constant in the sampling plane. If gas stratification levels are sufficiently low, and there is no direct correlation between regions of high and low concentration and high and low velocity, then for the accuracies desired, we may have

$$\overline{\mu_i} \cdot \overline{u_s} \approx \overline{\mu_i u_s} \tag{13}$$

If this approximation were generally valid, large savings on systems hardware requirements would be realized. It would mean that proportional sampling would not be required, which would allow for a simple constant flow rate sampling network. Further it would mean that gas sampling and volumetric flow, as designated by u_s, could be determined independently. Since Phase I results (Reference 1) showed that volumetric flow can be determined in complex ducts with as few as one velocity sensor, independent determination offers even greater advantages. As will be shown in subsequent sections of this report, the approximation represented by equation (13) proved to be very good for the data examined.

4.2.2 Stratification Assessment

In order to determine stratification levels from various sources in a consistent manner, a uniform method to determine measures of data spread

is required. Perhaps the most common and easy to work with measure of spread is the standard deviation for a normal distribution. The potential problem with using standard deviation as a measure of spread is that it is normally applied to a number of measurements of the same parameter, such as repeated measurements of the length of a table top, or repeated measurements of gas composition in a fixed volume with no chemical reaction. For the present case, we wish to apply it to a number of individual measurements of concentration at separate points in a non-uniform gas stream. For this case, there is no a priori reason to believe that the readings can all be considered to belong to a normal distribution. Gas traverse data obtained during the Phase I field test (Section VIII) were examined to see if they approximated a normal distribution. Data consisted of 49 point traverses for O_2, CO_2, and NO_x in a coal fired power plant. Actual data are presented in Section VIII. For each traverse, the mean value and standard deviation of the gas concentration was determined as follows:

$$\mu_i = \frac{1}{N}\sum_{n=1}^{N}(\mu_i)_n \tag{14}$$

where for the case N = 49.

$$\sigma_{\mu_i} = \sqrt{\frac{\sum_{n=1}[(\mu_i)_n - \overline{\mu_i}]^2}{N}} \tag{15}$$

where

σ_{μ_i} = standard deviation of μ_i

It is common, particularly for small values of N, to use (N-1) instead of N in the denominator of equation (15). For the purposes of this program, one or at most two significant figures are desired for σ, so that use of N instead of (N-1) has no significant effect on desired accuracy. Results of the calculations are shown in Table I. Results for all three cases are very close to what would be expected for a normal distribution. This is further illustrated in Figure 3 for the NO_x traverse. Figure 3 shows a histogram of deviations from the mean NO_x value. Superimposed on this is

Table 1. COMPARISON OF DEVIATIONS FOR ACTUAL AND NORMAL DISTRIBUTIONS

DEVIATION	NORMAL DISTRIBUTION	ACTUAL DISTRIBUTIONS		
		NO_X	CO_2	O_2
σ	68.3	65.3	61.2	71.4
2σ	95.4	100	100	89.8
3σ	99.7	100	100	100

Data for actual distributions taken from TRW field test. See Section VI.

Tabular values are percentage of data points which differ from the mean value by less than the specified deviation.

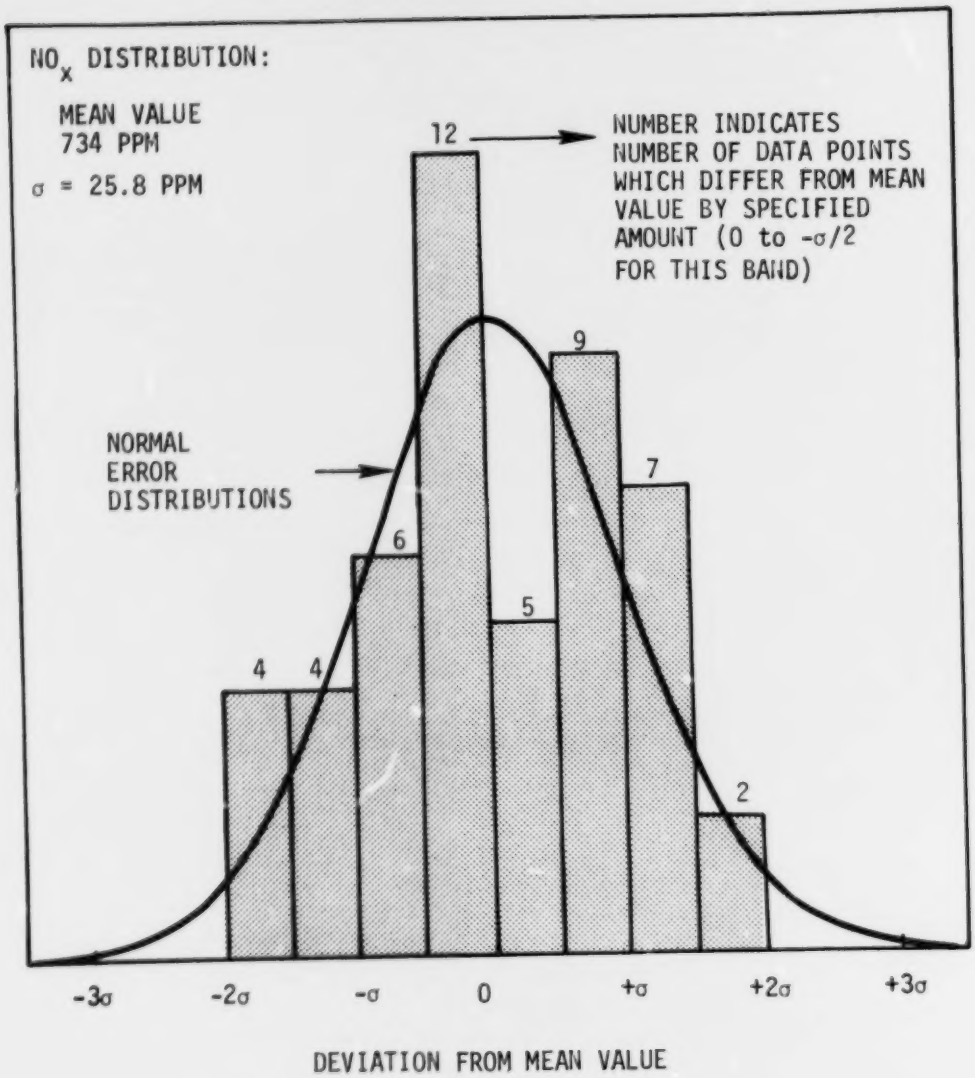


Figure 3. Histogram of deviations from mean value for NO_x traverse

the normal distribution curve. The conclusion reached from Table I and Figure 3 is that the standard deviation used is a reasonably accurate reflection of the actual data distribution.

Given the validity of the standard deviation as a measure of spread, we can now define a parameter to indicate the degree of stratification in a stream. For most engineering applications, a 95% level of certainty with regard to the accuracy of a measurement is acceptable. This corresponds to a band of $\pm 2\sigma$ about the mean value. Consider the NO_x traverse as an example. The mean concentration was 734 ppm with a standard deviation of $\pm$26 ppm, or 3.5%. By definition, then, we will say that the stratification level was $\pm$7% (i.e. 2σ) from the mean, which means that the probability is 95.4% that a point measurement taken anywhere in the sample plane will deviate from the mean concentration by less than $\pm$7%. Stratification level is being defined as $\pm 2\sigma$ from the mean concentration value in the sampling plane.

4.3 DESIRED SYSTEM ACCURACY

The proposed relation which we wish to consider for determing mass flow rates of gaseous constituents is

$$\dot{m}_i \approx \frac{AT_s}{Np_s} RM_i (\overline{\mu_i}) (\overline{u_s}) \tag{16}$$

The uncertainty in the measurement may be given by (see Reference 3 and/or Appendix A of Reference 1):

$$\sigma^2_{m_i} = \left(\frac{\partial \dot{m}_i}{\partial A}\right)^2 \sigma^2_A + \left(\frac{\partial m_i}{\partial \overline{\mu_i}}\right)^2 \sigma^2_{\overline{\mu_i}} + \left(\frac{\partial m_i}{\partial \overline{u_s}}\right)^2 \frac{\sigma^2}{u_s} \tag{17}$$

where

σ_x = standard deviation of parameter x.

The terms N, T_s, p_s, R, and M_i are considered to be known constants and as such are not error sources. Since each of the three variables is to be determined independently of the others, equation (17) can be written

$$\frac{\sigma^2_{m_i}}{m_i^2} = \frac{\sigma_A^2}{A^2} + \frac{\sigma^2_{\overline{\mu_i}}}{\overline{\mu}^2_i} + \frac{\sigma^2_{\overline{u_s}}}{\overline{u_s}^2} \tag{18}$$

The following assumptions may be made for normal field measurements:

$$\cdot \text{ Area: } \sigma_A = .01A$$

This is based on the assumption of a 2σ uncertainty of 1% in the duct linear dimensions.

$$\cdot \text{ Velocity: } \sigma_{\bar{u}_s} = .04\,\bar{u}_s$$

This is based on an assumed 2σ uncertainty of 8% for the average velocity as determined by techniques developed during Phase I of the program, using currently available hardware. Substituting, we get

$$\frac{\sigma^2_{\dot{m}_i}}{\dot{m}^2_i} = .0017 + \frac{\sigma^2_{\bar{\mu}_i}}{\bar{\mu}^2_i} \tag{19}$$

There are two main contributions to $\sigma_{\bar{\mu}_i}$: The sampling method error and the error associated with the sampling hardware itself. Typical continuous gas analyzers have published accuracies of about $\pm$1% of full scale. If we arbitrarily assume that averages readings will occur at about 50% of full scale, then the 2σ uncertainty for the instrument would be $\pm$2% of the reading. If we can obtain a 2σ uncertainty of $\pm$5% for the sampling method error, we would then have

$$\frac{\sigma^2_{m_i}}{\dot{m}_i^2} = .0017 + [(.01)^2 + (.025)^2] = .002425 \tag{20}$$

so that

$$\frac{\sigma_{\dot{m}_i}}{\dot{m}_i} = \pm .049 \tag{21}$$

and

$$2\sigma_{\dot{m}_i} = .098\,\dot{m}_i \tag{22}$$

which gives about a $\pm$10% uncertainty in the constituent mass flow rate. It must be noted that this uncertainty does not include errors due to the non-proportional sampling assumption underlying equation (16). If the

2σ error due to this assumption is $\pm 3\%$, then we get a $\pm 10.3\%$ uncertainty for the measurement of $\dot{m}_i$; if the 2σ error is $\pm 6\%$, then we get a $\pm 11.5\%$ uncertainty for $\dot{m}_i$.

The conclusion is that the greatest uncertainty lies in the measurement of the average velocity. While the $\pm 8\%$ uncertainty for this measurement can be reduced through careful selection of sampling locations (*if* a good one exists in the stream of interest), extensive in-place calibration, and/or very expensive equipment, the quoted figure represents a valid achievable level at reasonable cost. Preliminary determination of stratification levels suggests that it is reasonable to expect 2σ accuracies on the order of $\pm 6\%$ or better for the measurement of average concentration. This combines with the velocity uncertainty to give a basic constituent mass flow rate uncertainty of $\pm 10\%$. An additional uncertainty due to non-proportional sampling errors would perhaps raise the emission uncertainty to between $\pm 10.3\%$ and $\pm 11.5\%$. This accuracy level would appear to be reasonable for a continuous monitoring system. One additional point should be made, and that is that the accuracy of the total gas emission rate*, $\dot{m}$, will be better than the constituent mass flow rate $\dot{m}_i$ since the uncertainty in $\dot{m}$ is only slightly larger than that for $\bar{u}_s$. This is discussed in Reference 1. If $2\sigma_{\bar{u}_s} = \pm 8\%$ of $\bar{u}_s$, then we would expect $2\sigma_{\dot{m}} = \pm 8.4\%$ of $\dot{m}$.

* $$\dot{m} = \sum_{i=1}^{I} \dot{m}_i$$

SECTION V
TASK II FLOW ANALYSIS PROGRAM

The purpose of this task was to formulate a computer program to evaluate stratification data and determine the applicability of various sampling techniques. Expected program inputs would be arrays of gas concentration and velocity data. In Task I, the desirability of using the average spatial concentration as opposed to the proportional sampling average concentration was discussed, so it would be desirable for the program to investigate this area. Since Phase I work for velocity determination resulted in development of the Row Average technique, it was decided that the program should assess the applicability of this technique to gas sampling. The finalized program performed the desired analyses by using the basic input data to predict the local velocity and concentration at any desired point in the sampling plane.

5.1 PROGRAM DEVELOPMENT

When the program was conceptualized, there was little certainty regarding the best sampling techniques to be evaluated. Possible approaches included:

a. Walden's CO_2 tracer method

b. Multi-point proportional sampling

c. Multi-point spatial sampling

d. Single point sampling

e. Row Average sampling

f. Use of sampling data to predict a better sampling site further downstream.

It was decided that the basic program should at a minimum compute proportional and spatial sampling mean values, and have the capability to determine local values at any point in the sampling plane. This eventually resulted in the capacity to evaluate approaches b-e. The CO_2 trace method was evaluated separately, and is discussed in Section VI. Approach f

would involve mixing calculations to predict lower stratification levels at a given distance downstream. The extent of stratification in the data examined was low enough that this approach was not felt to be justified.

The final program configuration incorporates the following features:

- Expansion of input data matrix into a 525 point (21 x 25) matrix
- Calculation of average velocity, average spatial concentration, and proportional average concentration
- Calculation of 21 row averages across the duct
- Computation of profiles of constant concentration in intervals of 5% of the mean value

The program as it exists could easily be modified to evaluate the performance of any proposed sampling array for either spatial or proportional sampling. Due to the acceptability of the results for the Row Average technique, other methods have not been investigated during the program.

5.2 PROGRAM DESCRIPTION

The program itself is presented in Appendix A. The following is a description of the program and how it performs. Major steps in the program are:

1. Data Input - Arrays of velocity and concentration data are entered.
2. Array Expansion - The input arrays are expanded to 25 x 21 arrays using a TRW developed subprogram to interpolate between input points and determine values for the larger arrays. The subroutine is TRW BVIC (Bivariate Interpolation Subroutine), which uses polynomial interpolation to calculate the local values from the input values. The program assumes that the concentrations and velocities can be described by continuous single valued functions everywhere in the plane, which is physically realistic. For the input

arrays, there were no data taken at the duct walls, so no boundary conditions (i.e. conditions at the wall) were input. It is of course recognized that the velocity must always be zero at the wall. It has also be recognized that for the data considered, the flows were very non-developed, and consequently thin boundary layers would be present since there was no opportunity for them to become significantly large. It is felt that ignoring boundary layer development (other than that which showed up in the input data itself) by not specifying a no-slip condition at the wall leads to smaller errors than would be obtained with that boundary condition. It is believed that imposition of a no-slip condition would lead to inaccurately low predicted velocities near the wall.

3. Calculation of Averages - Using the 25 x 21 arrays, the program calculates three sets of 21 row averages: velocity, flow proportional concentration, and spatial concentration. In each case, the 25 points along each line are averaged using Simpson's rule. The 21 row averages are then averaged in the same way to produce the three mean values.

4. Calculation of Profiles - The program takes the mean flow proportional concentration and velocity and calculates values in 5% intervals on either side of the mean. It then uses the BVIC subroutine described above to calculate the points in the sampling plane corresponding to the locus of each specified interval. The purpose of this is to provide data which can be presented in the form of a concentration map, showing profiles in 5% increments from the mean. This allows for quick visual inspection of the sampling data, including stratification level, distribution of concentrations in the duct, and comparisons of data for various constituents and temporal variations of any one gas.

5.3 TYPICAL PROGRAM RESULTS

Results for CO_2 sampling by an Exxon team are shown in Table 2 and Figures 4 and 5. The test is discussed in more detail in Section VI. The duct measured 3.182m x 8.269m, and a 6 x 8 sampling array was used. The first part of Table 2 shows results of calculations based on the 48 sampling points. The CO_2 stratification level, defined by 2σ, was $\pm 11\%$ of the mean CO_2 value. The second part of the table shows results from the computer program. As would be expected, the computer results agreed very closely with the sample point results. Of particular note is the fact that the spatial mean values agreed with the flow proportional mean values to within 1%. Profiles for the run are plotted in Figure 5. The maximum deviations from the mean are about +15% and -25% of the mean value. Row averages, where a row is being defined as a line parallel to the short sides of the duct (vertical in Figure 5) are shown in Figure 4. The plot shows that row averages taken between 5% and 85% of the distance from the left wall deviate from the mean flow proportional concentration by 3% or less. All row averages plotted are spatial averages.

Table 2. TYPICAL ANALYSIS PROGRAM RESULTS

Exxon Run 1 - CO_2 Data

Direct calculations from field measurements:
48 point array (6 x 8)

SPATIAL CO_2 MEAN VALUE	13.83% of dry gas
STRATIFICATION LEVEL, 2σ	$\pm$11% of mean value
FLOW PROPORTIONAL AVERAGE	13.71% of dry gas

Computer Calculations:

273 point array (13 x 21)

SPATIAL CO_2 MEAN VALUE	13.82% of dry gas
FLOW PROPORTIONAL AVERAGE	13.69% of dry gas

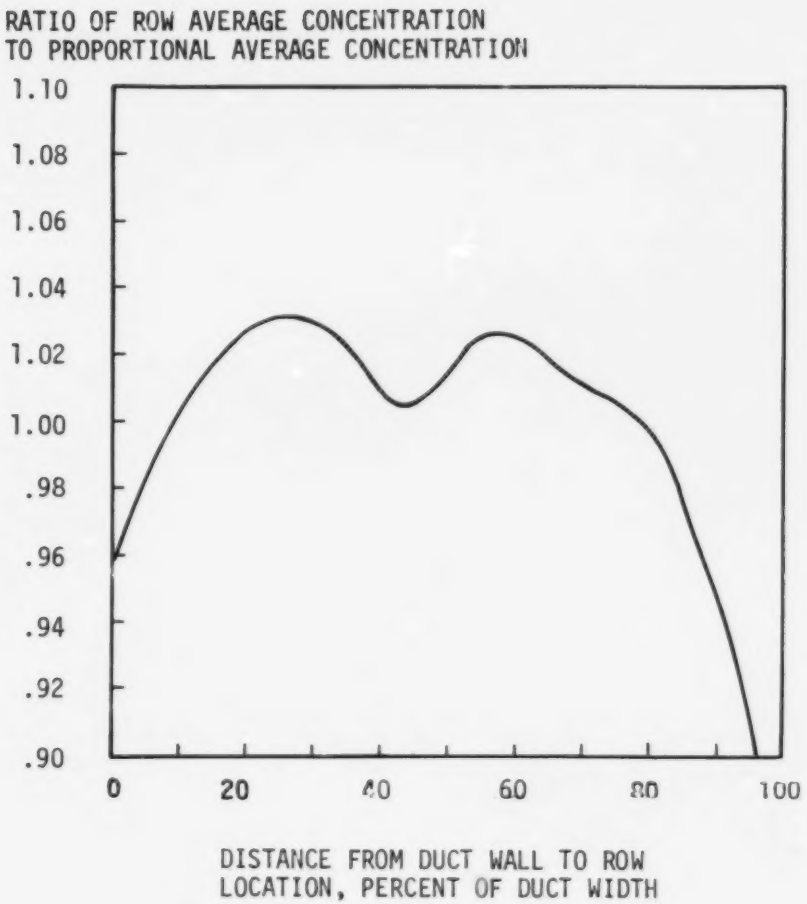


Figure 4. Row Average analysis for CO_2 concentration map--Exxon run 1

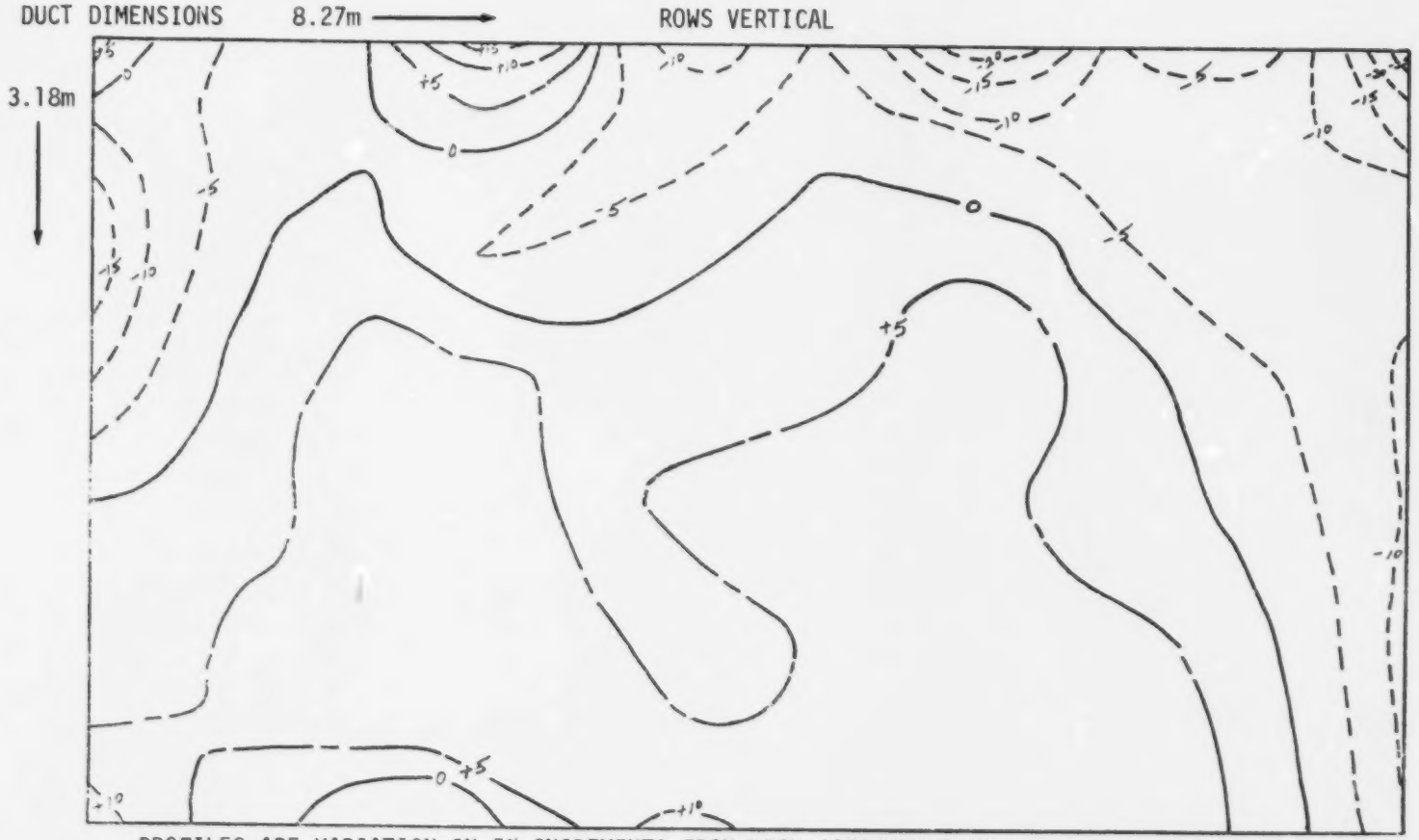


Figure 5. Normalized CO_2 concentration distribution--Exxon run 1

SECTION VI
TASK III MAPPING TECHNIQUE EVALUATION

This task involved analytical evaluation of continuous gas sampling techniques. Two separate groups of data were involved: one was obtained through the courtesy of Mr. Michael Gregory of Exxon Research and Engineering Company and Dr. Mike Barnes of EPA. The data were obtained at TVA's Widows Creek Unit No. 7, under EPA Contract No. 68-02-1722, which is concerned with stratification assessment in fossil fueled power plants. The examined data consisted of two traverses for velocity and for CO_2, SO_2, NO, and O_2 concentrations. The data are hereafter referred to as the Exxon data. The second data group were obtained from the Walden stratified gas final report, and consist of four sets of velocity and SO_2 concentration data obtained at a TVA power plant in Shawnee, Kentucky. These data are referred to as the TVA data.

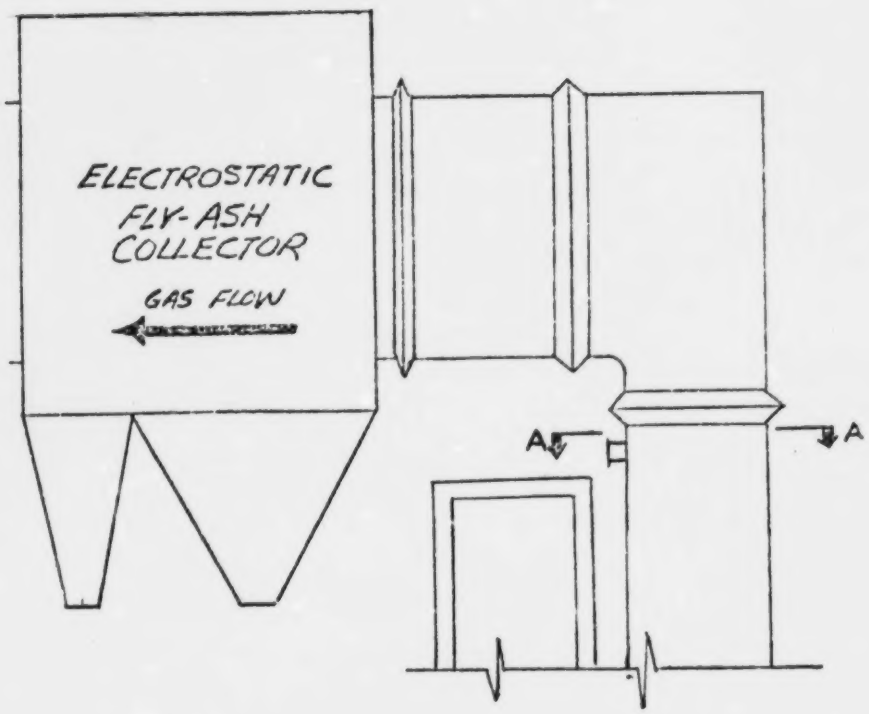
The data were analyzed through use of the computer program described in the last section. In addition, the Exxon data were used to evaluate the Walden CO_2 tracer technique. Results are presented and discussed below.

6.1 EXXON DATA

The sample plane location is shown in Figure 6. It was located approximately 1.6 effective diameters downstream of an elbow. The duct cross-section is shown in Figure 7. The raw velocity data were changed to velocity at standard conditions, and the raw gas composition data were used directly.

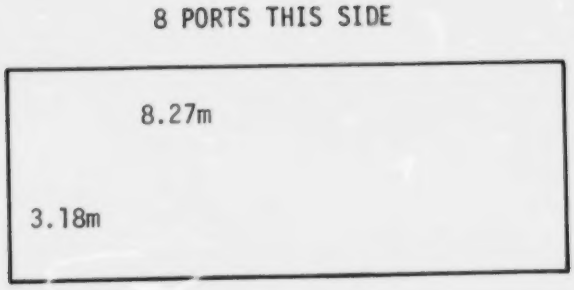
6.1.1 Concentration Maps

Concentration data are presented in Figures 8-15 (4 gases - 2 runs each). Maps are shown as normalized concentration distribution, with lines representing deviation from the mean flow proportional concentration. The SO_2 and NO maps, Figures 10-13, did not show recognizable repeatable patterns. The CO_2 and O_2 maps, Figures 8, 9, 14, and 15, did show a predominance of excess air on the right side of the duct, which

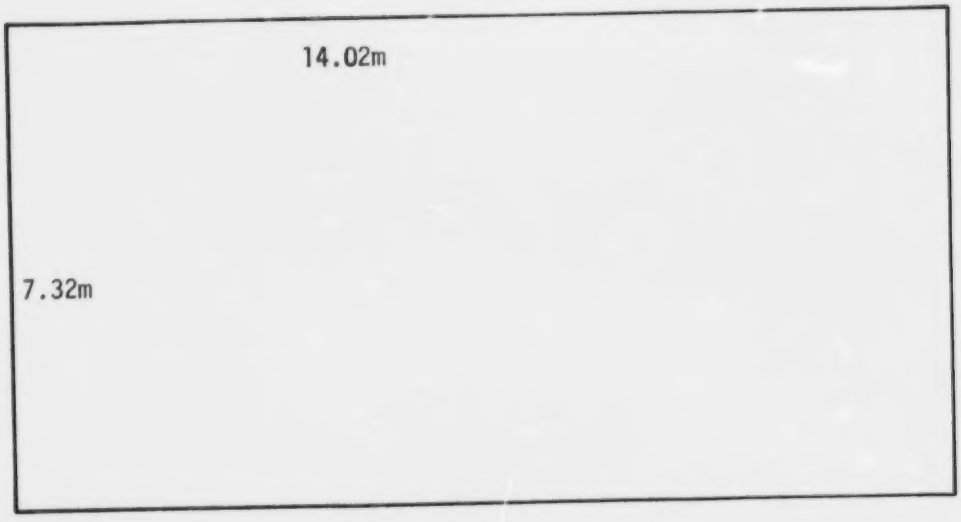


Sample plane located at A-A.
Short side of duct in plane of paper.

Figure 6. Location of sampling plane for Exxon data - TVA Widows Creek Unit 7

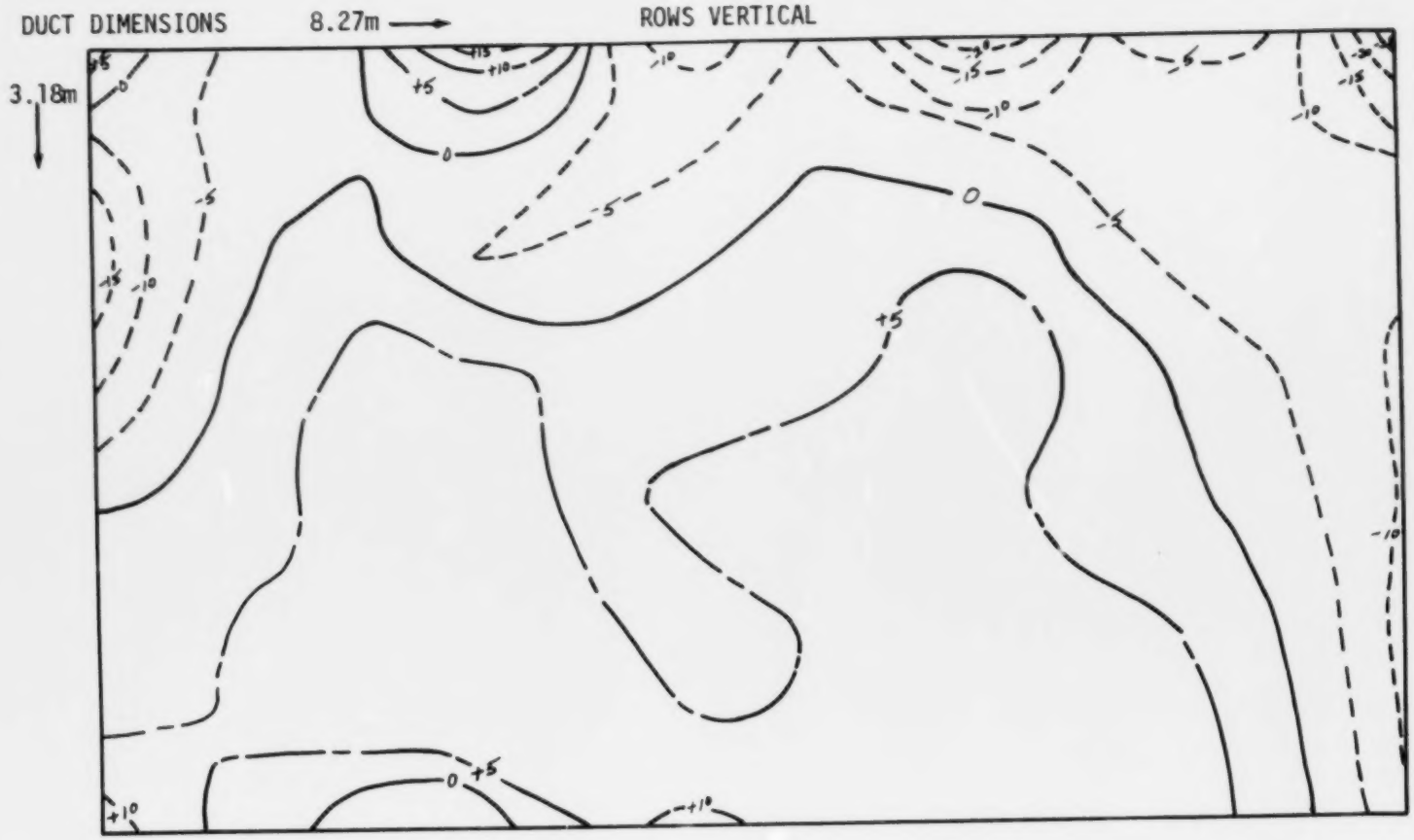


A. Duct for Exxon Tests



B. Duct for TVA Tests

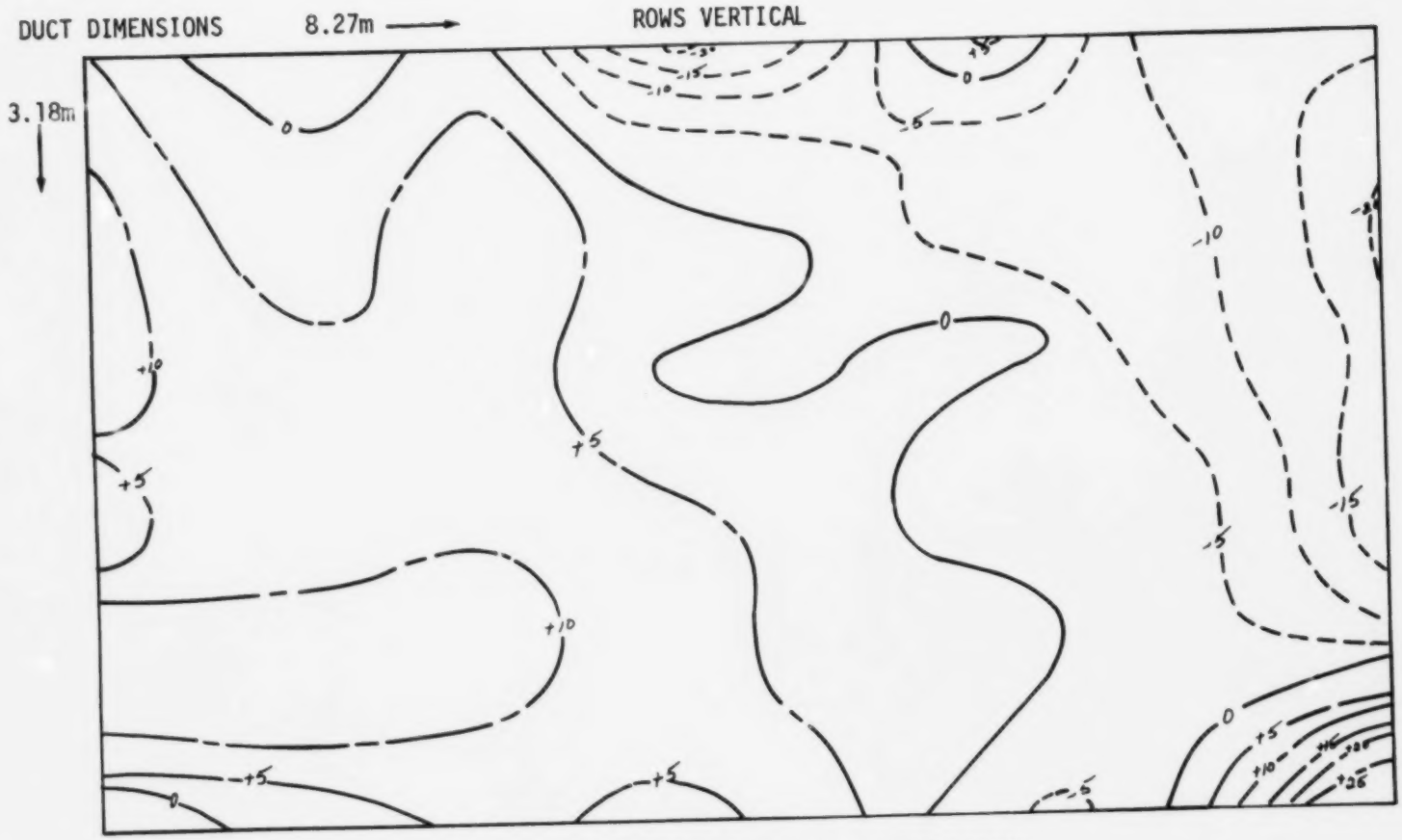
Figure 7. Duct shapes for Exxon and TVA tests



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 13.69% (DRY GAS)

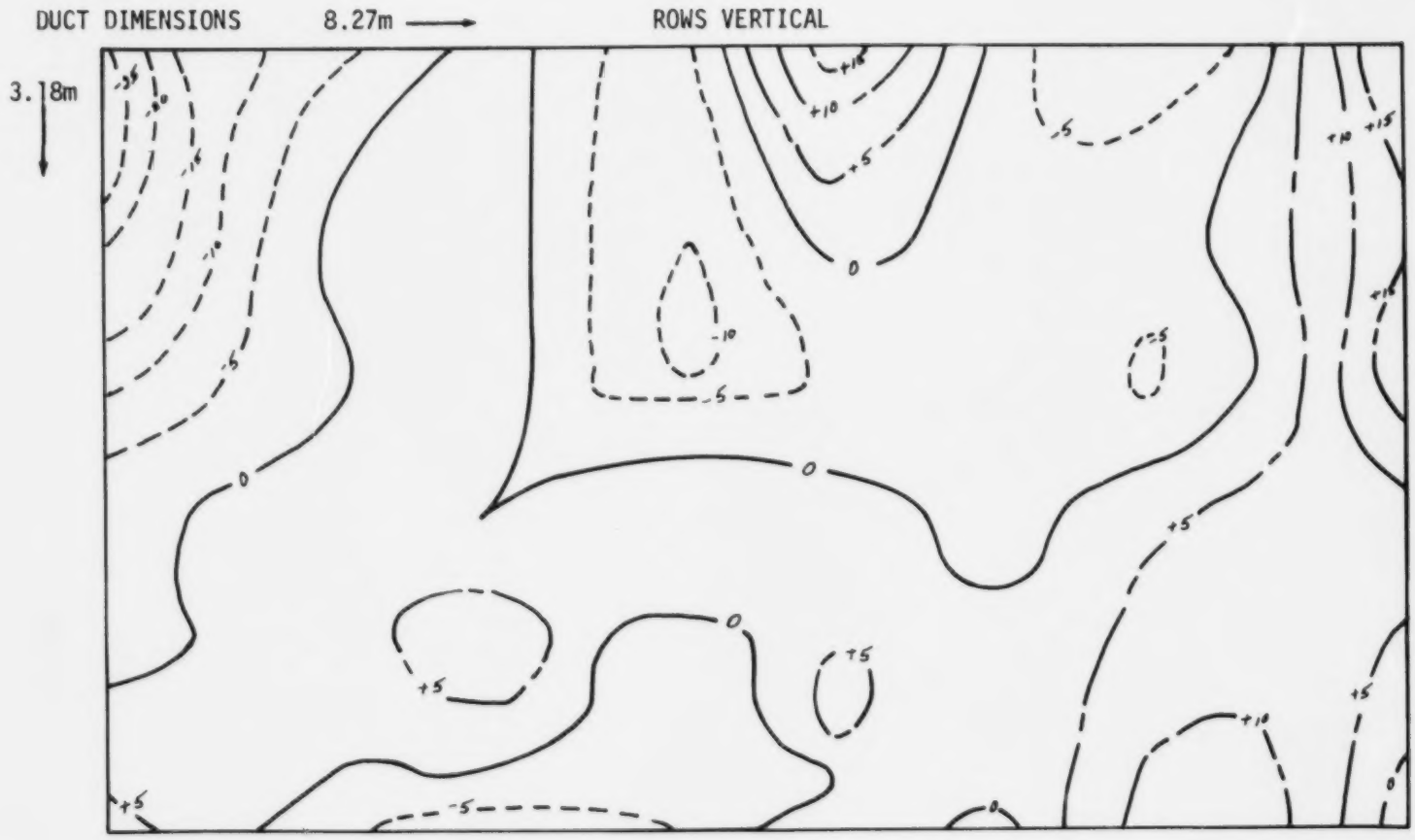
Figure 8. Normalized CO_2 concentration distribution--Exxon run 1



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 12.77% (DRY GAS)

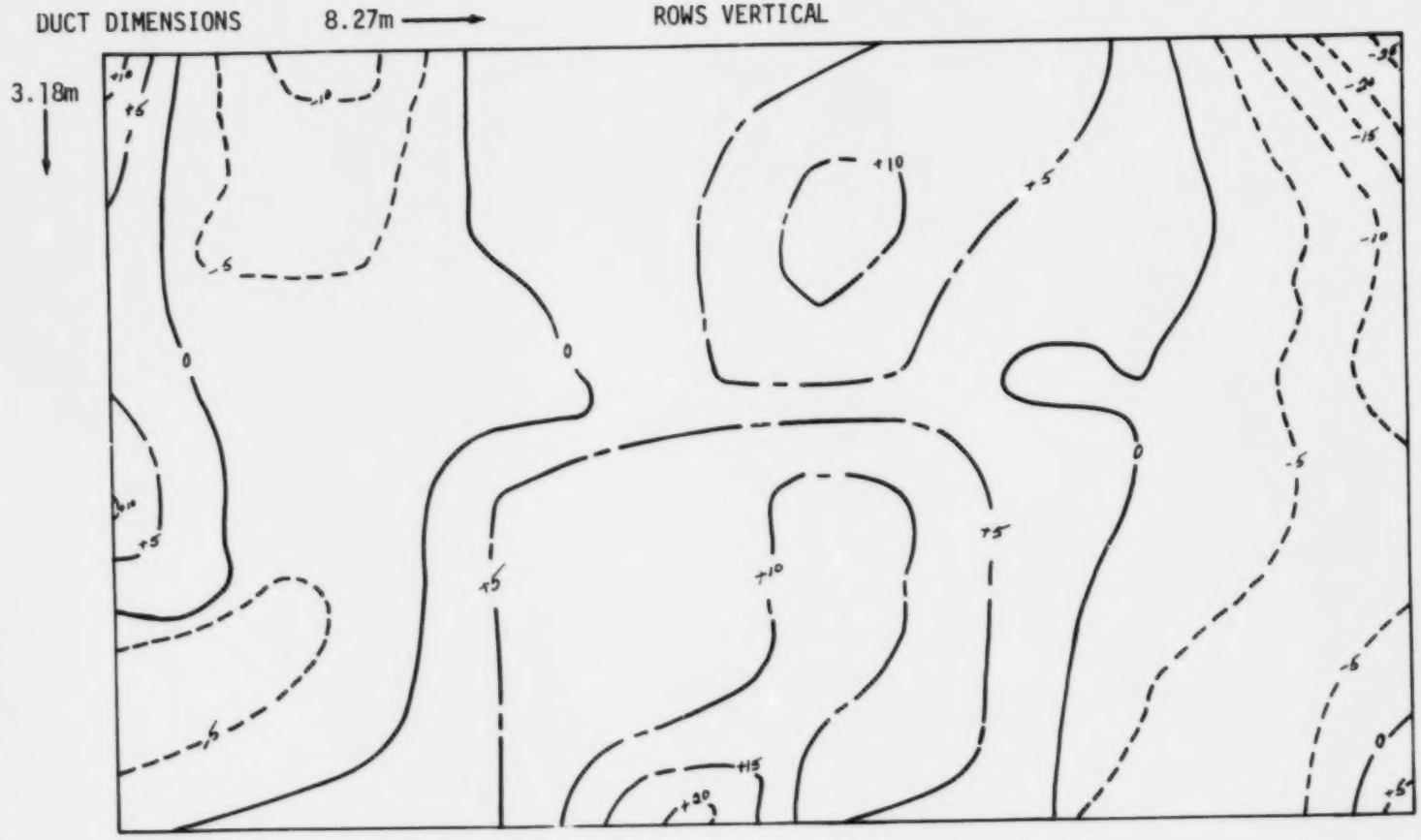
Figure 9. Normalized CO_2 concentration distribution--Exxon run 2



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 2706 PPM

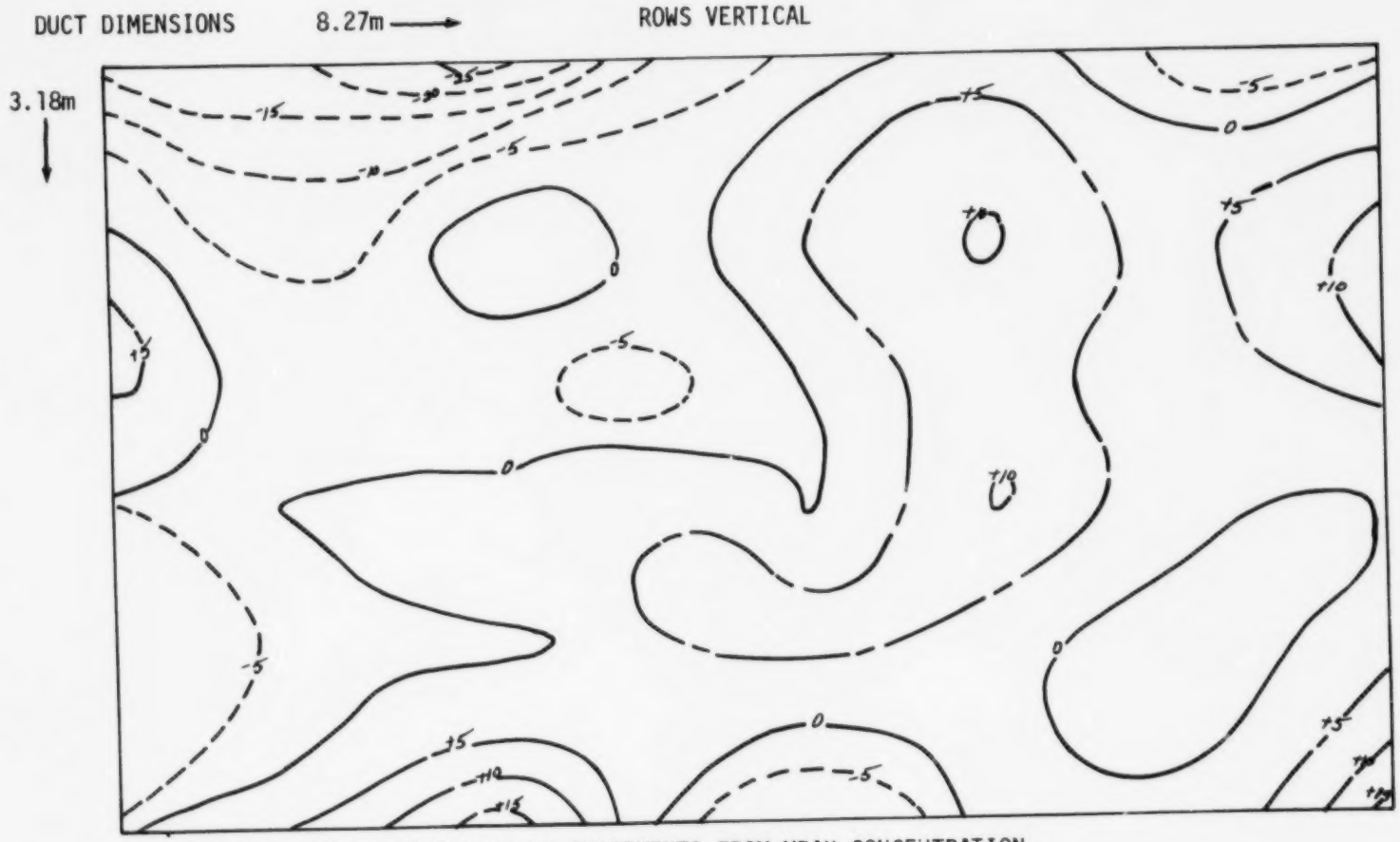
Figure 10. Normalized SO_2 concentration distribution--Exxon run 1



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 2042 PPM

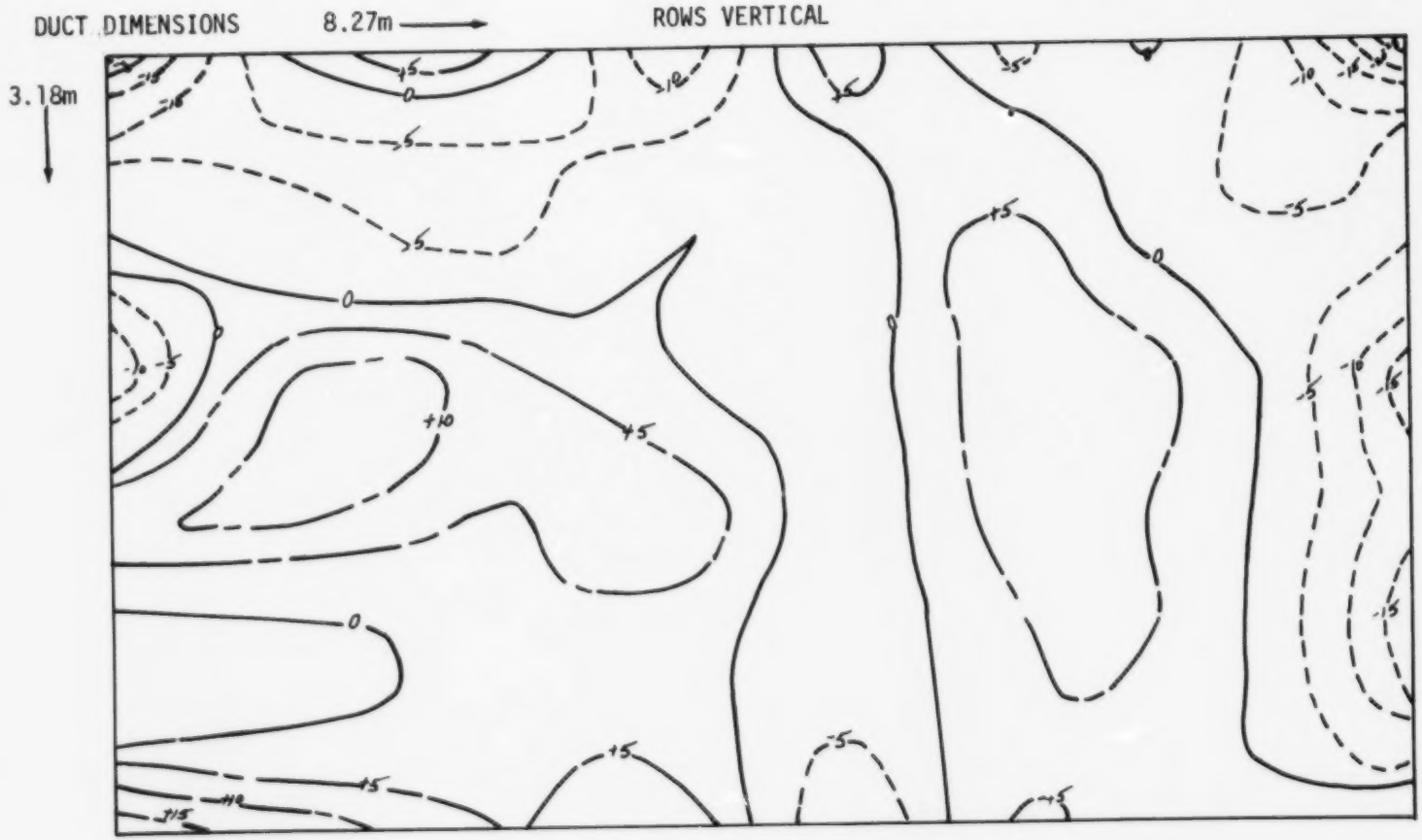
Figure 11. Normalized SO_2 concentration distribution--Exxon run 2



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 305.3 PPM

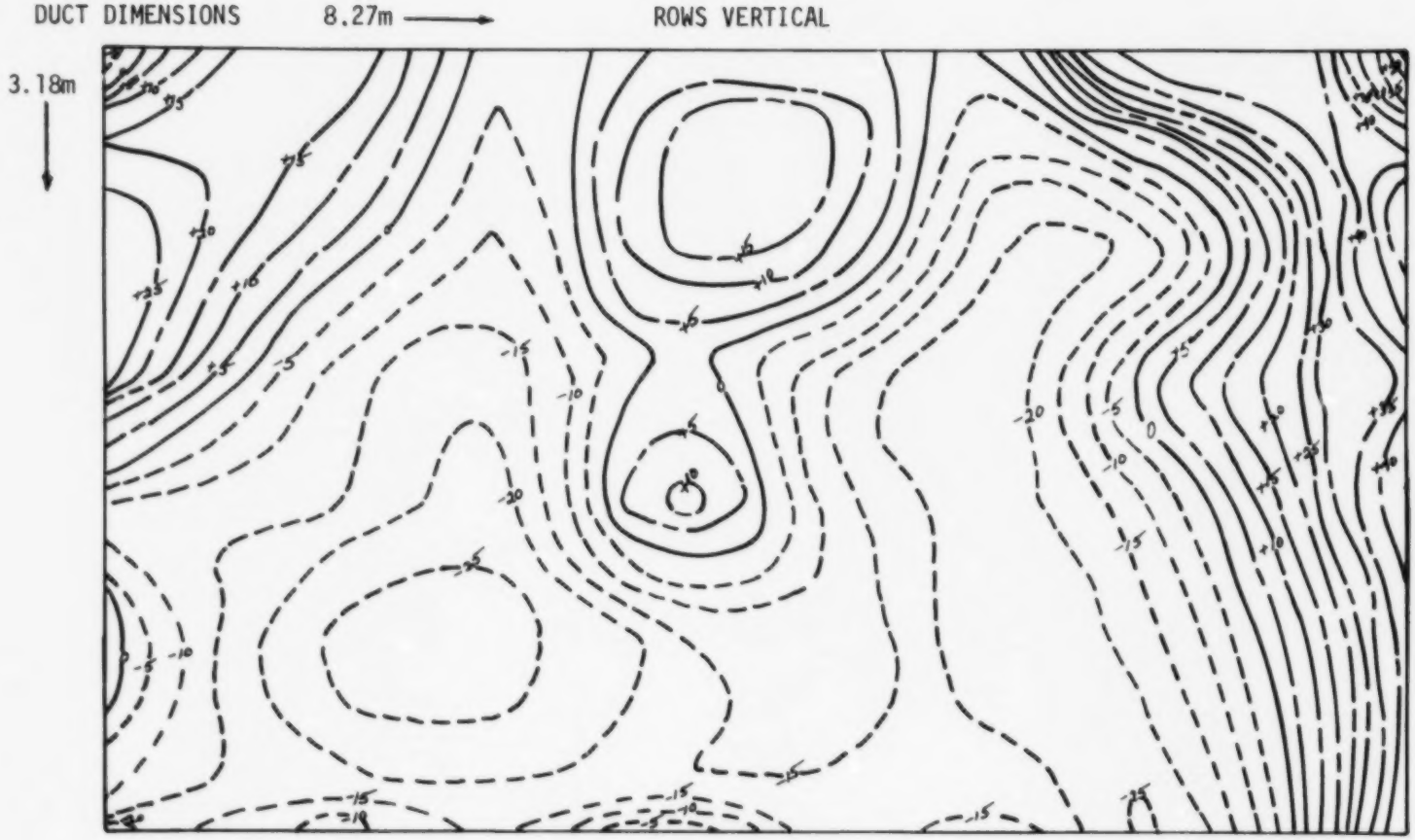
Figure 12. Normalized NO concentration distribution--Exxon run 1



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

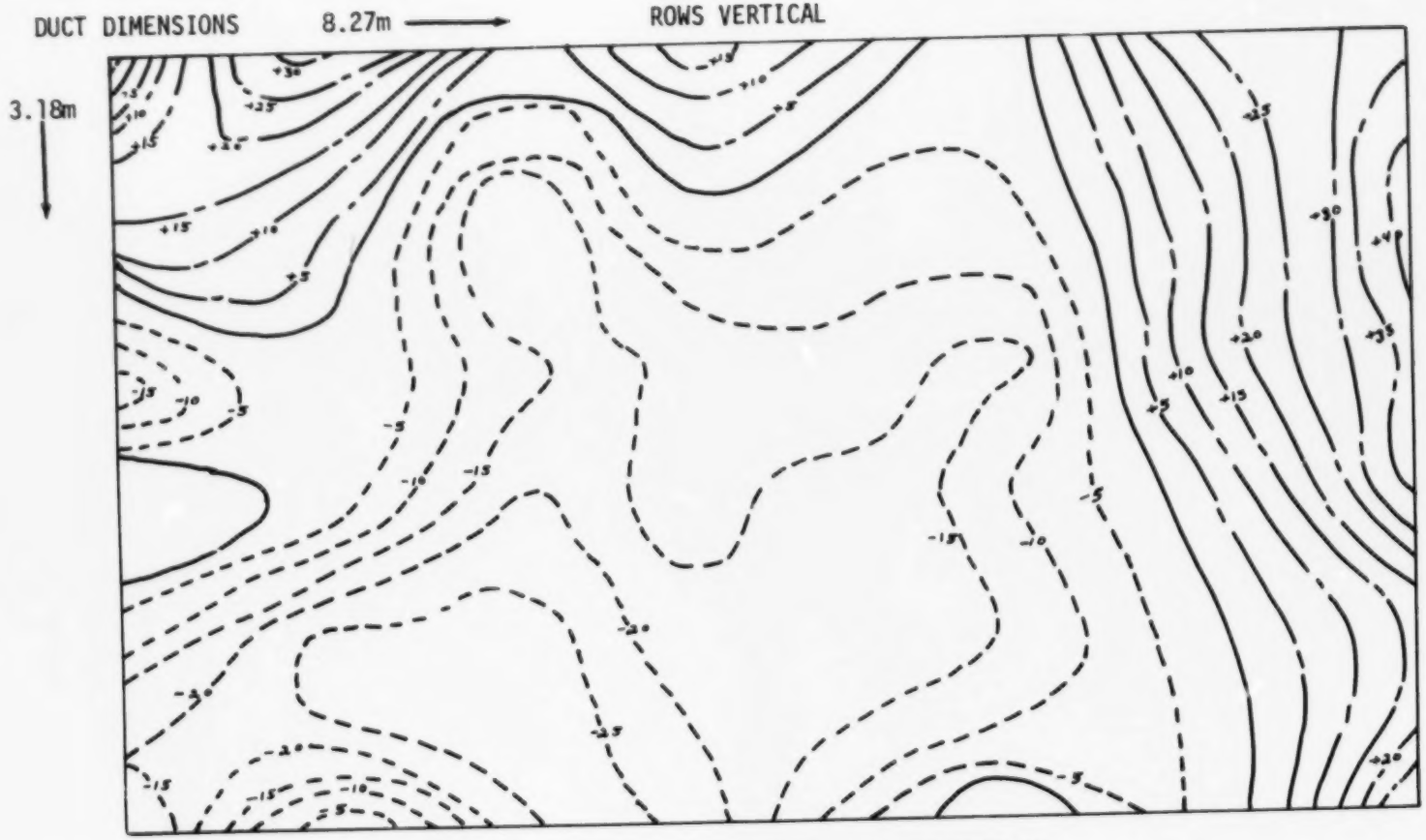
MEASURED MEAN CONCENTRATION = 322.5 ppm

Figure 13. Normalized NO concentration distribution--Exxon run 2



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION
MEASURED MEAN CONCENTRATION = 4.36% (DRY GAS)

Figure 14. Normalized O_2 concentration distribution--Exxon run 1



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 4.56% (DRY GAS)

Figure 15. Normalized O_2 concentration distribution--Exxon run 2

showed up as high O_2 values and low CO_2 values. Plant geometry would appear to suggest air leakage ahead of the sample plane as the cause for this stratification. There is no obvious explanation for the high SO_2 and NO levels toward the right side for the first run. The high O_2 levels would seem to suggest that the SO_2 and NO levels should be low, as they were for the second run.

The maps clearly show that O_2 was the most stratified of the gases. Since O_2 and CO_2 together make up about 20% of the dry gas composition, and since the mean CO_2 concentration is made higher than the O_2 concentration, it would be expected that the oxygen stratification would be greater than that for CO_2. The maps suggest similar stratification levels for CO_2, NO, and SO_2,

6.1.2 Mean Values and Stratification Levels

Mean values of gas concentration and stratification levels are shown in Table 3. Calculations from actual data points agreed with computer calculations within 1% for all cases. Of particular note is the fact that the spatial and flow proportional averages were in very close agreement -- the only variations larger than 1.1% were for oxygen, where the variation was less than 4%. This shows almost negligible coupling between velocity and concentration and leads to the preliminary conclusion that proportional sampling is not required for accurate measurements.

Stratification levels, as defined in Section IV, were on the order of $\pm$10% of the mean value for CO_2, SO_2, and NO and were about $\pm$34% for O_2. The higher O_2 stratification level was expected, as discussed above. Velocity stratification was notably higher than gas stratification: the level was above $\pm$65% of the mean velocity. For all gases, the stratification level was sufficiently high to discourage suggesting that simple point monitoring would be adequate, especially since the concentration maps did not show good repeatability.

6.1.3 Evaluation of CO_2 Tracer Method

For each of the two runs, the ratios of SO_2 and NO concentrations to CO_2 concentration were calculated at each of the 48 traverse points. The mean ratio and standard deviation were then calculated. The deviations

Table 3. MEAN VALUES AND STRATIFICATION LEVELS FOR EXXON DATA

	Velocity, m/sec		CO_2, %		SO_2, ppm		NO, ppm		O_2, %	
MEAN VALUES	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2
FROM DATA POINTS										
Spatial	4.957	4.400	13.83	12.91	2712	2063	307.1	324.4	4.217	4.379
Flow Proportional	-	-	13.71	12.79	2705	2039	305.2	323.3	4.355	4.548
FROM COMPUTER										
Spatial	4.912	4.364	13.82	12.91	2711	2063	307.0	324.2	4.235	4.390
Flow Proportional	-	-	13.69	12.77	2706	2042	305.3	322.5	4.364	4.560
STRATIFICATION LEVEL, 2σ, % of mean value	±65.7	±70.2	±11.0	±14.6	±11.8	±12.4	±10.6	±10.8	±36.4	±32.2

Maximum variation between spatial and flow proportional average = 3.9%

Average variation between spatial and flow proportional average = 1.4%

in percent of the mean value are shown in Table 4. For each case, the 2σ deviation shown is about 50% higher than the stratification level of the gases, which suggests that uniformity of the ratios is not good.

6.1.4 Row Average Evaluation

For this analysis, rows were selected parallel to the short sides of the duct. This was done for several reasons. The first is that this is the same direction in which velocity row averages would be taken (see Reference 1). Other reasons are strictly practical: a row average could be acquired through use of a single continuous sampling probe, as described in Section VII. Existing ports in the duct are in the long side, which suggests that one of these ports could be used to install the probe, or at the least that there would be access if a new port were needed. Also, it would be much easier to handle a three meterprobe than an eight meter probe.

Row average data are shown in Figure 16. Results are not quite as good as had been hoped. As discussed in Reference 1, the Row Average technique works well for velocity measurement when the flow is conditioned to give fairly constant row averages across the duct. For velocity, this occurs immediately downstream of an elbow. For gas sampling, there is no common mechanism which conditions the flow in an analogous manner. The CO_2 row averages for run 1 show a desirable pattern: the row average deviates from the overall average by less than 3% over most of the duct. Conclusions to be drawn are that repeatability between runs 1 and 2 was not good, as noted previously, and that more uniform row averages would be obtained if the rows were taken horizontal instead of vertical in Figures 8-15. The latter is clear because there is obviously greater stratification from right to left than from top to bottom in those figures. The first rule established for selection of row directions for velocity measurement was that the rows should be parallel to the direction of greatest stratification. It is unfortunately true for these runs that the direction of highest gas stratification is perpendicular to the direction of highest velocity stratification.

The problem of poor temporal repeatability could not be reasonably assessed through analysis of only two runs, so the following TVA data were examined primarily for that purpose.

Table 4. CO_2 TRACER METHOD ANALYSIS OF EXXON DATA

	2σ, % of mean value
RUN 1	
SO_2/CO_2	$\pm$15.2
NO/CO_2	$\pm$16.0
RUN 2	
SO_2/CO_2	$\pm$16.6
NO/CO_2	$\pm$15.2

Explanation of tabular values:

2σ = $\pm$15.2% of mean value for SO_2/CO_2 ratio means that there is a 95.4% probability that the ratio of the SO_2 reading to the CO_2 reading at any point in the duct will agree with the average SO_2/CO_2 ratio within $\pm$15.2%

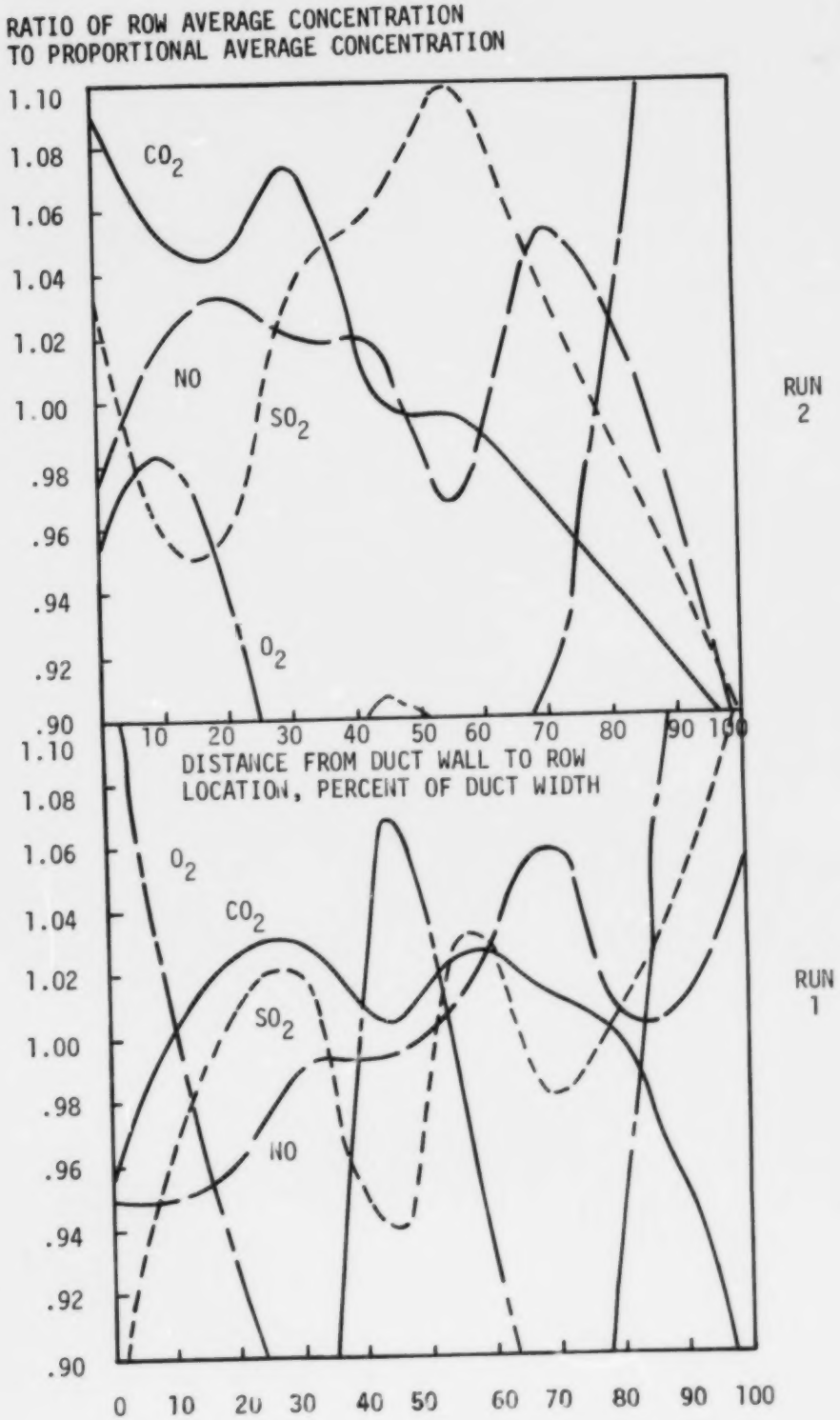


Figure 16. Row average analysis for gas concentration maps--Exxon runs 1 and 2

6.2 TVA DATA

No drawings were available showing location of the sample plane. The duct cross-sectional shape is shown in Figure 7. A total of four pairs of SO_2 and velocity maps was examined. The velocity data were not obtained simultaneously with the SO_2 data, but it is felt that this does not compromise the results to be discussed.

6.2.1 Concentration Maps

Concentration data are presented in Figures 17-20, using the same format as for the Exxon data. There are again no immediately recognizable stratification patterns among the runs. Stratification does appear to be greater in the vertical than in the horizontal direction.

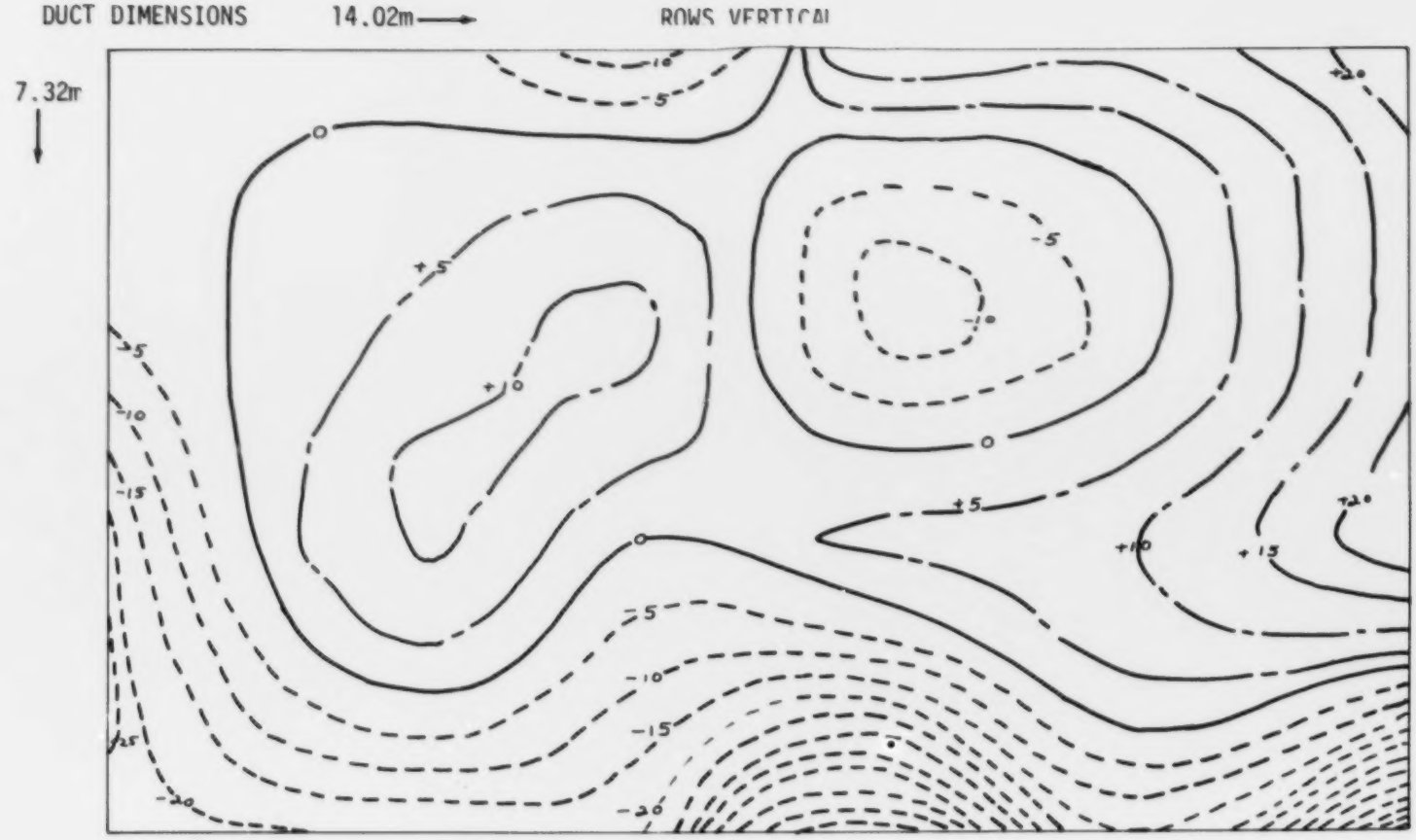
6.2.2 Mean Values and Stratification Levels

These values are shown in Table 5. Agreement between actual data point calculations and computer calculations was not quite so good as for the Exxon data. This is presumably due to the fact that the TVA traverses used only 24 points (4 x 6), whereas the Exxon traverses involved 48 points (6 x 8). The 1.75% average variation between spatial and flow proportional mean concentrations is compatible with the Exxon results, and continues to demonstrate the adequacy of spatial sampling. It would appear that the variation is proportional to the stratification level in the gas -- both the variation and the stratification level for the TVA data are higher than for the Exxon CO_2, NO, and SO_2 data, but lower than for the Exxon O_2 data.

6.2.3 Row Average Evaluation

Row Average data are presented in Figure 21.

The first three runs do not exhibit as great a uniformity as would be desired, but do show fairly good repeatability. The change in shape on the left side of the duct in Run 4 is clearly undesirable. A row average taken at the center of the duct would show good correlation for all four runs -- much better than would be attained for the Exxon data.



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 2011 PPM

Figure 17. Normalized SO_2 concentration distribution--TVA run 1

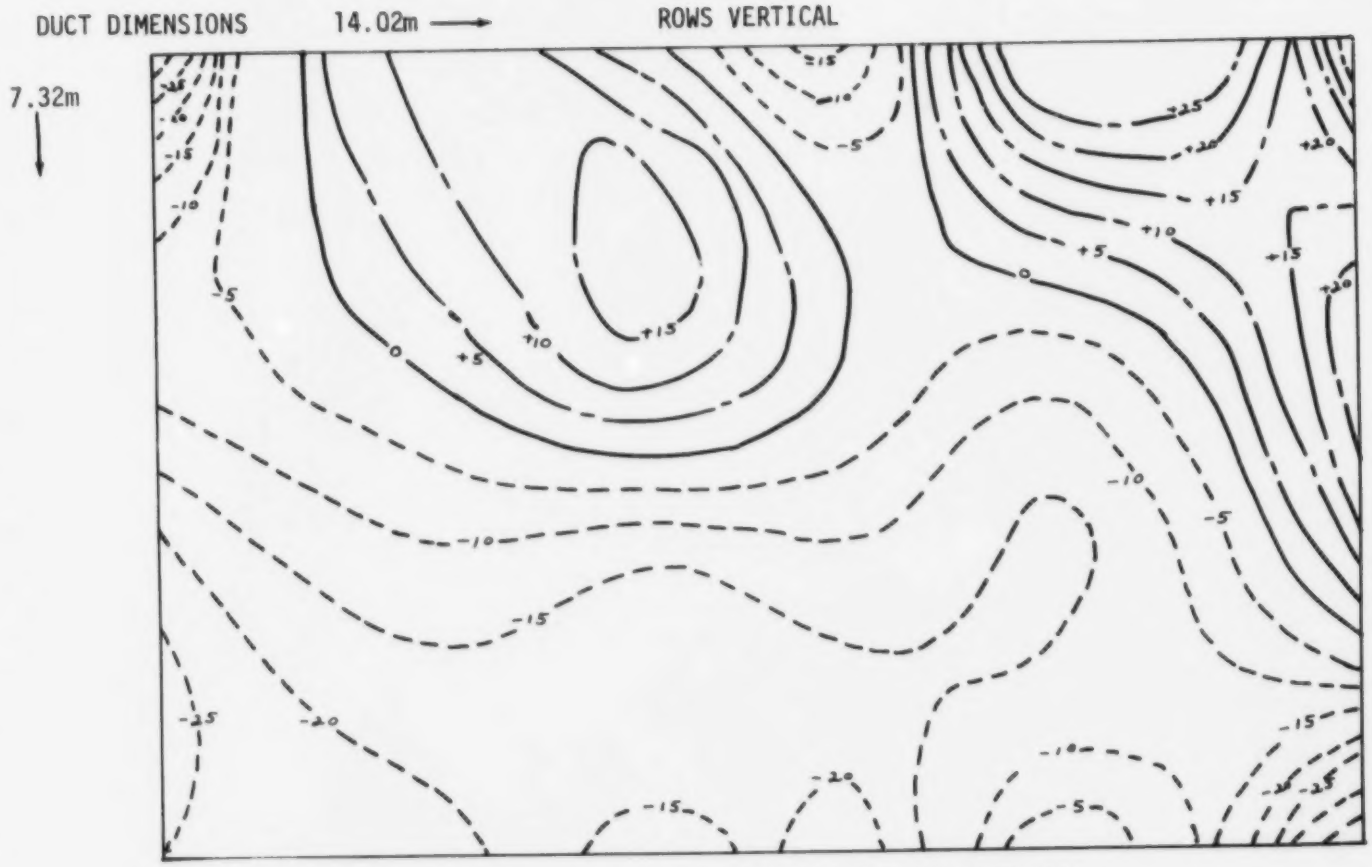
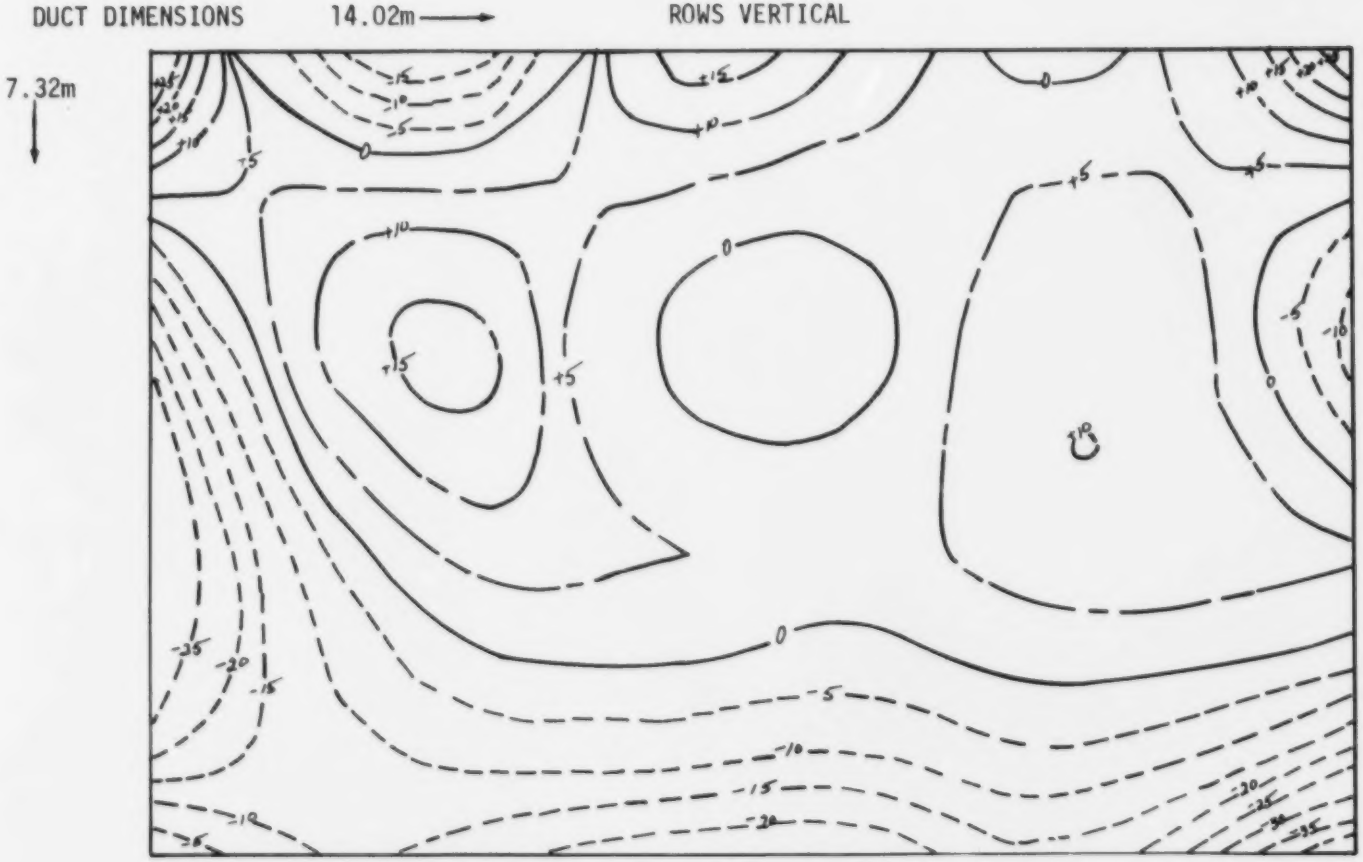


Figure 18. Normalized SO_2 concentration distribution--TVA run 2



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 2100 PPM

Figure 19. Normalized SO_2 concentration distribution--TVA run 3

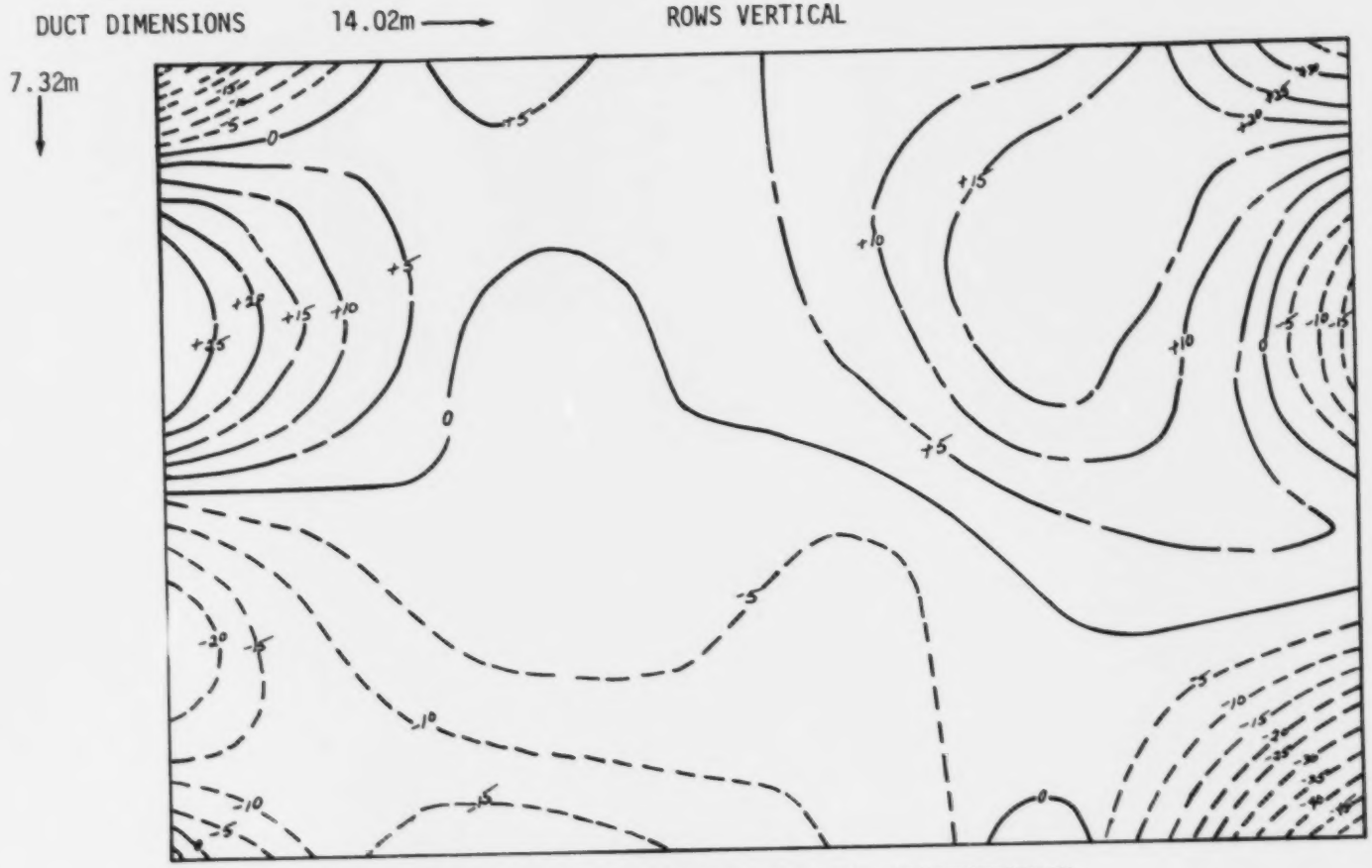


Figure 20. Normalized SO_2 concentration distribution--TVA run 4

Table 5. MEAN VALUES AND STRATIFICATION LEVELS FOR TVA SO_2 CONCENTRATION DATA

MEAN VALUES, PPM OF SO_2	RUN			
	1	2	3	4
FROM DATA POINTS				
Spatial	2059.5	2204.4	2099.7	2036.5
Flow Proportional	2056.9	2207.2	2109.2	2047.5
FROM COMPUTER				
Spatial	1982.5	2085.0	2071.9	2029.5
Flow Proportional	2011.2	2148.7	2100.3	2054.5
STRATIFICATION LEVEL, 2σ, % of mean value	$\pm$20.4	$\pm$26.5	$\pm$17.1	$\pm$19.7

Average variation between spatial and flow proportional average = 1.75%

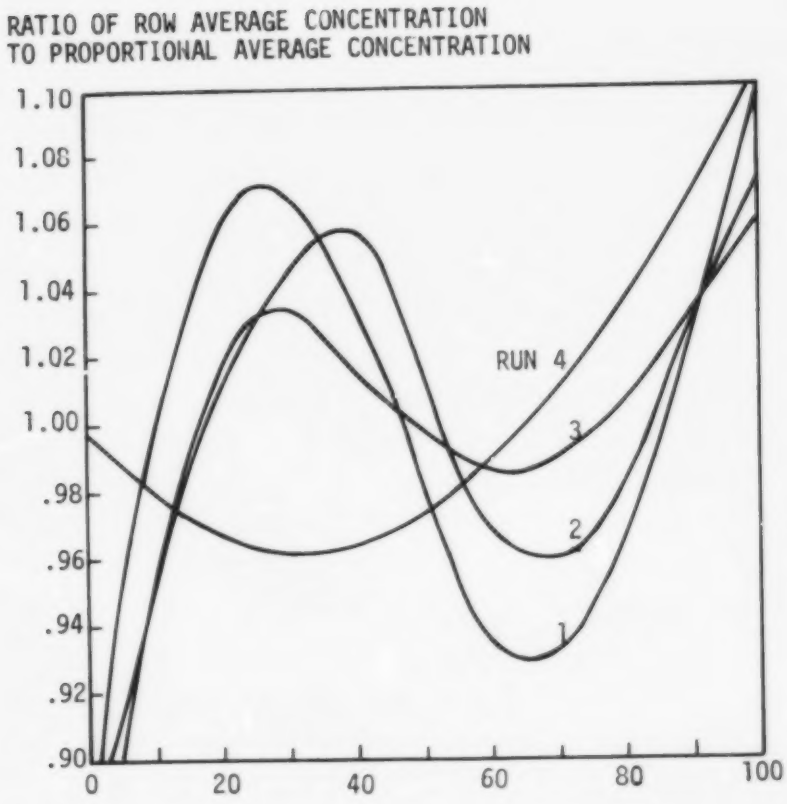


Figure 21. Row average analysis for SO_2 concentration maps--TVA runs 1-4

6.3 PRELIMINARY SAMPLING TECHNIQUE CONCLUSIONS

For any given gas concentration distribution, it is a trivial matter to select a sampling array which would obtain a representative sample. Problems arise when more than one gas species must be sampled, and when the gas distributions change as a function of time. The greatest difficulty with regard to continuous gas sampling is to effectively handle the temporal changes, since they cannot be predicted easily if at all. Temporal changes in velocity distributions are not such a problem. Velocity distribution is primarily a function of local duct geometry, which is normally fixed. Changes in gas distribution are much more a function of combustion characteristics and air leakage.

Two major conclusions are apparent from the data examined. The first is that stratification levels were too high to justify single point sampling for a continuous monitoring system. The stratification level itself is a measure of how accurate a single point sample is likely to be. For the twelve runs examined, the mean stratification level, 2σ, was $\pm$ 18.6%, which is far from the proposed desired accuracy of $\pm$ 6% for average concentration. Single point sampling is also intuitively more prone to temporal variation errors than any multi point sampling system. As a general rule, single point sampling should only be considered acceptable in situations where the stratification level is not worse than the desired accuracy of the concentration measurement.

The other conclusion is that spatial gas sampling is as accurate in determining effluent rates as flow proportional sampling, within about 2%. This justifies development of continuous monitoring systems which acquire spatial samples, rather than more difficult (therefore expensive) flow proportional samples. The spatial sampling method examined has been the Row Average method, which showed reasonably good results for the TVA data, but poorer results for the Exxon data. One reason for the latter was high stratification levels normal to the adopted row direction. Agreement between concentration levels of SO_2 and NO with respect to CO_2 was rather poor for the Exxon data. It was decided at this point to select the Row Average technique for field evaluation, due to its simplicity and easy adaption to hardware, as well as due to the promising results from the TVA data analysis.

SECTION VII
TASK IV SAMPLE PROBE DEVELOPMENT

The Row Average technique for gas sampling was discussed in the previous section. The next objective was to develop a sampling probe to satisfy the requirements of Row Average sampling. In this section, probe design requirements are formulated mathematically and fabrication of a prototype probe for the field demonstration is discussed. Also included are suggestions for improved probe designs.

7.1 PROTOTYPE PROBE DESIGN

One of the continuous sampling techniques considered in Section VI was the Row Average method. Since this method is probably the easiest one to develop hardware for, it was decided to produce prototype sampling probes for the Phase II field demonstration described in Section VIII. The basic design criteria for such a probe are quite simple:

- The probe should draw samples at a number of evenly spaced points along a line across the duct.
- The same sample rate should be maintained at each sampling point.
- The samples from each point should be mixed and drawn out through a single sampling line.

The probe design is illustrated in Figure 22. A small sampling hole was located at each of eight preselected locations corresponding to an even distribution along the probe. It was decided that control of flow distributuion among the holes would be accomplished by making the holes small enough that the pressure drop across each hole would be large compared to pressure changes along either the inside or outside of the probe. Mixing of the acquired samples from each port would clearly be accomplished within the probe body. The most direct alternative to the technique used would be to have a separate sample line from each point. Each line would then need a control value and flowmeter to insure equal

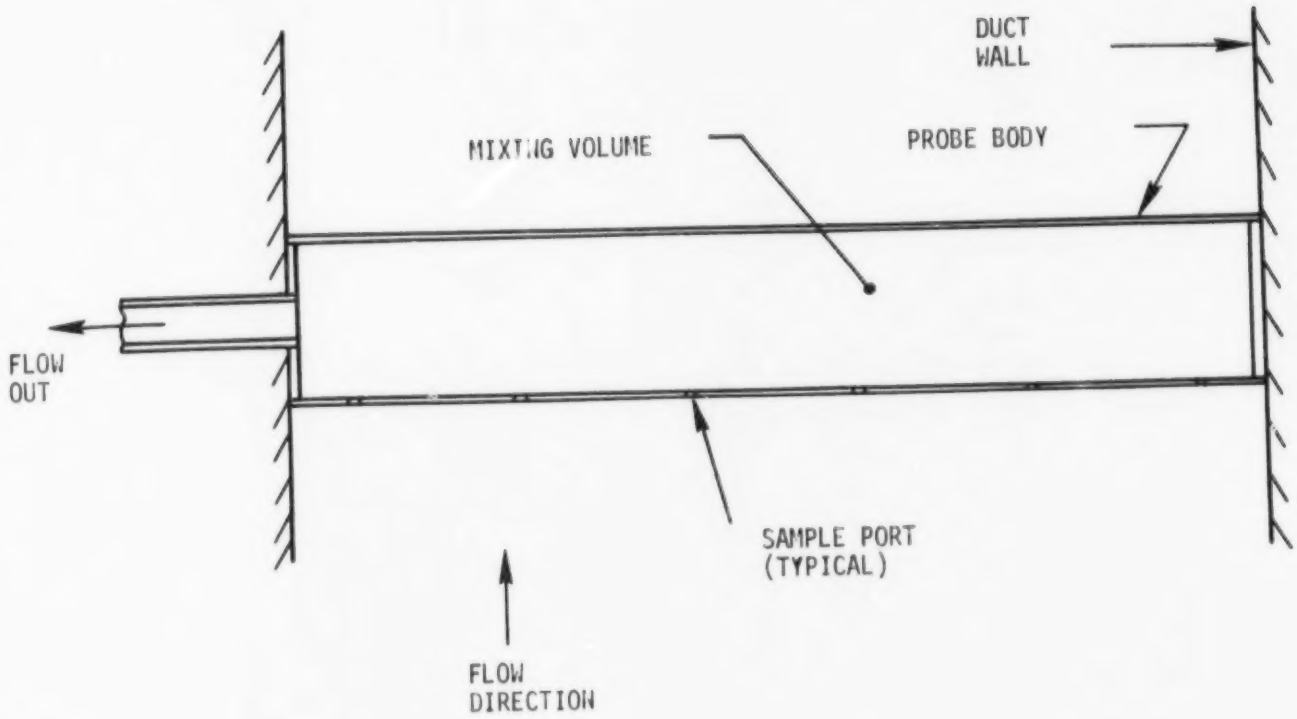


Figure 22. Multi-port sampling probe basic design

flow from each point. The lines would then feed into a suitable plenum chamber and be mixed for delivery to the analyzers.

Once the number and location of sampling holes have been selected, the only major analytical task is to select the hole sizes. This proceeded as follows:

- Determination of worst case pressure variation

  Outside the probe: The Phase II field demonstration was to be conducted at the same power plant as the Phase I field test (see Section VIII). The maximum observed velocity during the Phase I test was about 11 m/sec, which corresponded to a differential pressure of $p_o - p_\infty = \Delta p = .75$ torr. A sample flow rate of .5 l/sec ($\sim$1 CFM) was selected, along with a probe size of 2.54 cm (1 in.). This corresponded to a maximum flow velocity within the probe of about 1.2 m/sec. Since this was considerably below the expected variation in freestream conditions outside the probe, the external conditions determined the maximum expected pressure variation.

- Desired pressure drop across orifices

  It was arbitrarily decided that the duct pressure variation should not be more than 5% of the pressure variation across the sampling ports. This meant that the latter should be at best 20 x .75 torr = 15 torr.

- Determination of hole diameter

The sample volumetric flow is given by

$$\dot{V} = n\bar{v}\,(.61A) \tag{23}$$

where $\dot{V}$ = volumetric flow

n = number of sampling ports

$\bar{v}$ = average velocity of gas through sample ports

A = sample port area

.61 = sample port discharge coefficient

In terms of the pressure drop in the orifices, this becomes

$$\dot{V} = .61\ (\tfrac{\pi}{4})d^2 n \sqrt{2RT\ (\frac{p_o}{p_\infty} - 1)} \tag{24}$$

where d = hole diameter

R = gas constant

T = absolute temperature

p_o = absolute pressure ahead of orifice

p_∞ = static pressure in orifice

Solving for d, we get

$$d = \left(\frac{\dot{V}}{15.69n \sqrt{T_\infty\ (\frac{p_o}{p_\infty} - 1)}} \right)^{1/2} \tag{25}$$

If $\dot{V}$ = .5 l/sec

n = 8

T_∞ = 450°K

p_o = 715 torr

p_∞ = 715-15 = 700 torr

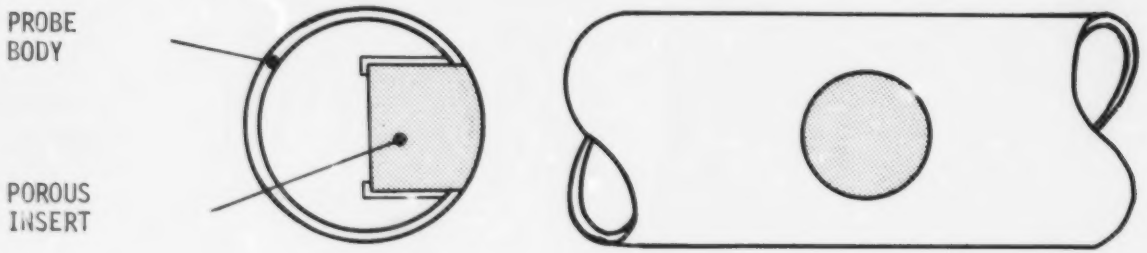
then d = 1.295 mm (.051 inches)

The nearest drill size was a #55 drill, 1.32 mm (.052 inches) diameter, so this size was used. See Section VIII for discussion of actual probe use.

7.2 SUGGESTIONS FOR IMPROVED PROBE DESIGN

The above design showed its capability to avoid clogging of the orifices with particulate, as discussed in Section VIII. The problem which did show up, however, was a buildup of particulate within the probe. In an operational continuous monitoring system, such problems would be unacceptable. It would appear that the only reasonable way to handle the particulate problem would be to filter out the particulate before it can enter the probe. Probe inlets to accomplish this are shown in Figure 23. In each case, the key element is the filter. The operating

A. At each specified sampling point, a porous filter insert is installed. Uniformity of pressure drop, hence flow rate, is assured through control of insert porosity.



B. A combination filter/liner is used to obtain a sample along the entire probe length. This assumes that a true Row Average sample is acquired. The filter and liner form a one piece bonded unit.

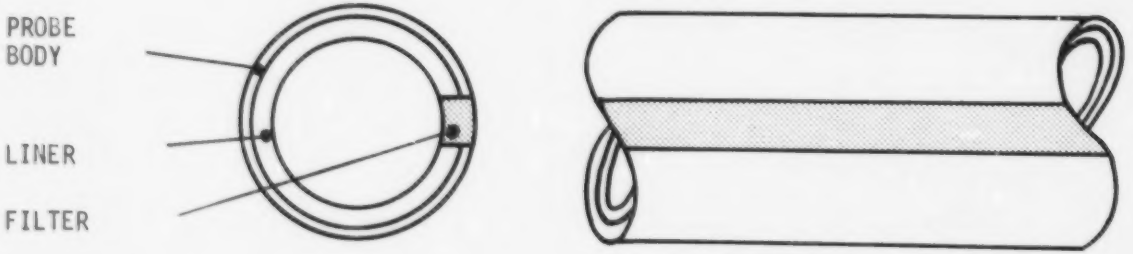


Figure 23. Suggestions for continuous gas sample probe modifications to prevent particulate entry into the probe

principle is exactly the same as for the fabricated probe: the pressure drop must be identical through each section and must be large compared with external pressure variations. This requires uniformity of the filter.

So long as the particulate is reasonably dry, a slow rate of buildup would be expected on the filters since a self-cleaning effect was noted on the prototype unit. To clean the probe, an automatic intermittent purge capability should be provided as part of the instrumentation system. The purge intervals would be determined by the application, and the accumulated dust would be blown back into the main stream. This type of purge system was successfully demonstrated in a different application as part of the Phase II field test (see Reference 1).

Recent TRW experience with Kapton liners for sampling probes and our knowledge of properties of various high temperature polymers suggests that such materials may be quite applicable in the production of filters for the application in Figure 23. The desirable properties of polymers for this application include chemical inertness and physical integrity for temperature as high as 500°C. They are also castable into any desirable shape, and it is believed that very accurate control of pore sizes can be obtained. The latter is the property which controls pressure drop across the filter.

SECTION VIII
TASK V - FIELD DEMONSTRATIONS

The task objective was to demonstrate the applicability of techniques and hardware for continuous gas sampling. Two field demonstrations were performed at the Reid-Gardner Station of the Nevada Power Company, located at Moapa, Nevada. The plant is about 72 km. northeast of Las Vegas. Each test lasted about eighteen days. The first was begun in September, 1974, and the second was begun in February, 1975. The primary purpose of the first test was to demonstrate hardware and techniques for volumetric flow measurement which had been successfully tested in the laboratory. Gas sampling data were taken in support of the volumetric flow measurements and to assess stratification levels. The primary purpose of the second test was to demonstrate techniques and hardware for continuous gas sampling. Volumetric flow measurements have been fully documented in Reference 1. Only flow data pertinent to this report are discussed below.

8.1 FACILITY DESCRIPTION

The plant presently consists of two Foster-Wheeler 120 megawatt boilers, with a third under construction. All work was performed on the #2 unit, shown schematically in Figure 24. Flow from the boiler is separated into two streams which pass through Lunjstrom rotary air preheaters. The ducts at the two preheater outlets go through a shape transition and then rejoin upon entering a mechanical dust collector. A row of test ports is located on each duct just ahead of the dust collector. This is shown in Figure 25. All rectangular duct mapping was done at these locations.

When the plant was first constructed, the dust collector exhausted directly into the stack. Subsequently, a venturi scrubber and separator were added by Combustion Equipment Associates. When the scrubber is on, the flue gas is diverted at the dust collector exit and routed to the scrubber, where it is processed and fed into the stacks. If the scrubber is not on, the flue gas goes directly into the stack after leaving the dust collector. The inlet to the stack is about 13 m above ground level.

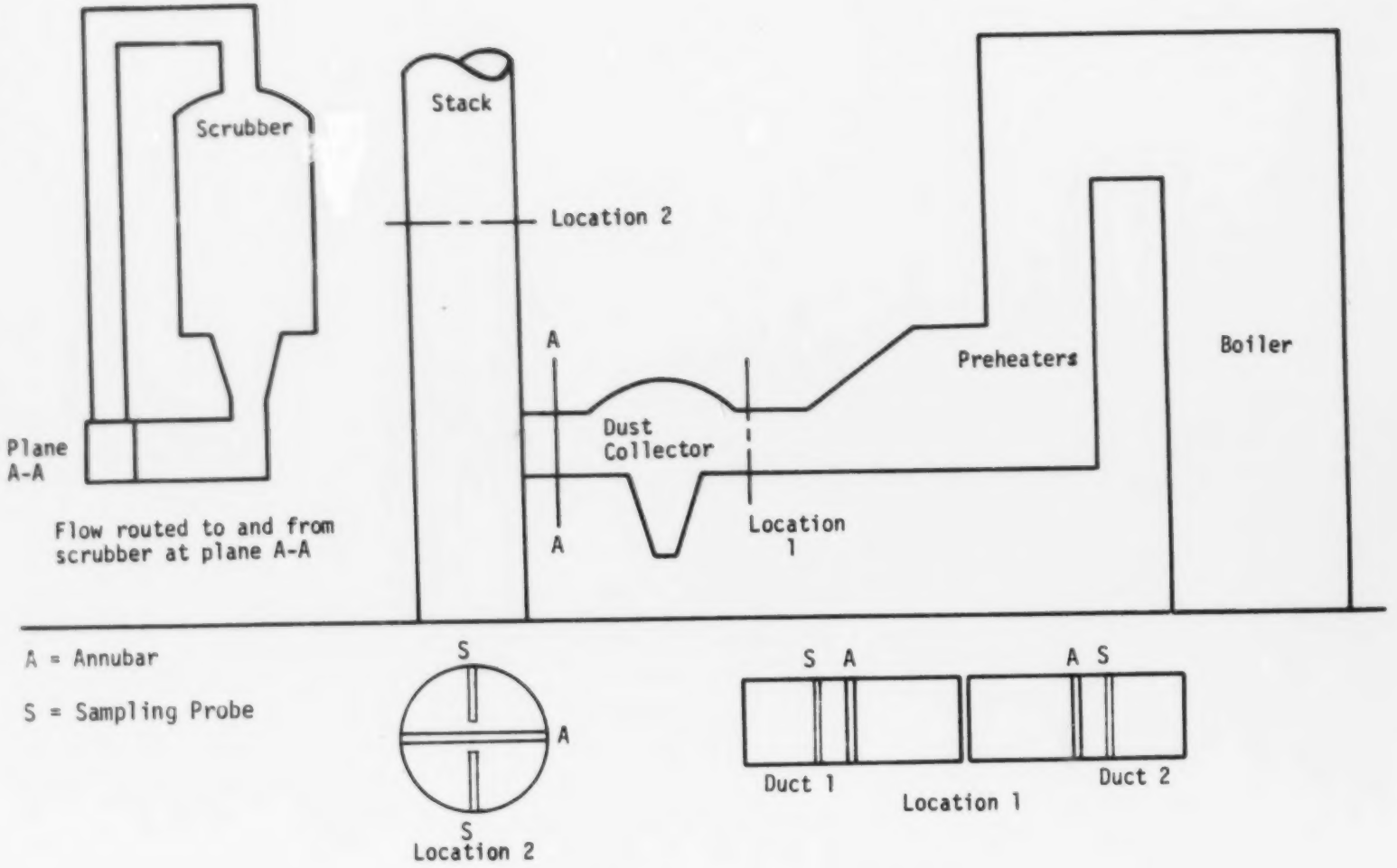


Figure 24. Schematic of Moapa power plant

Duct 2 is a mirror image of duct 1

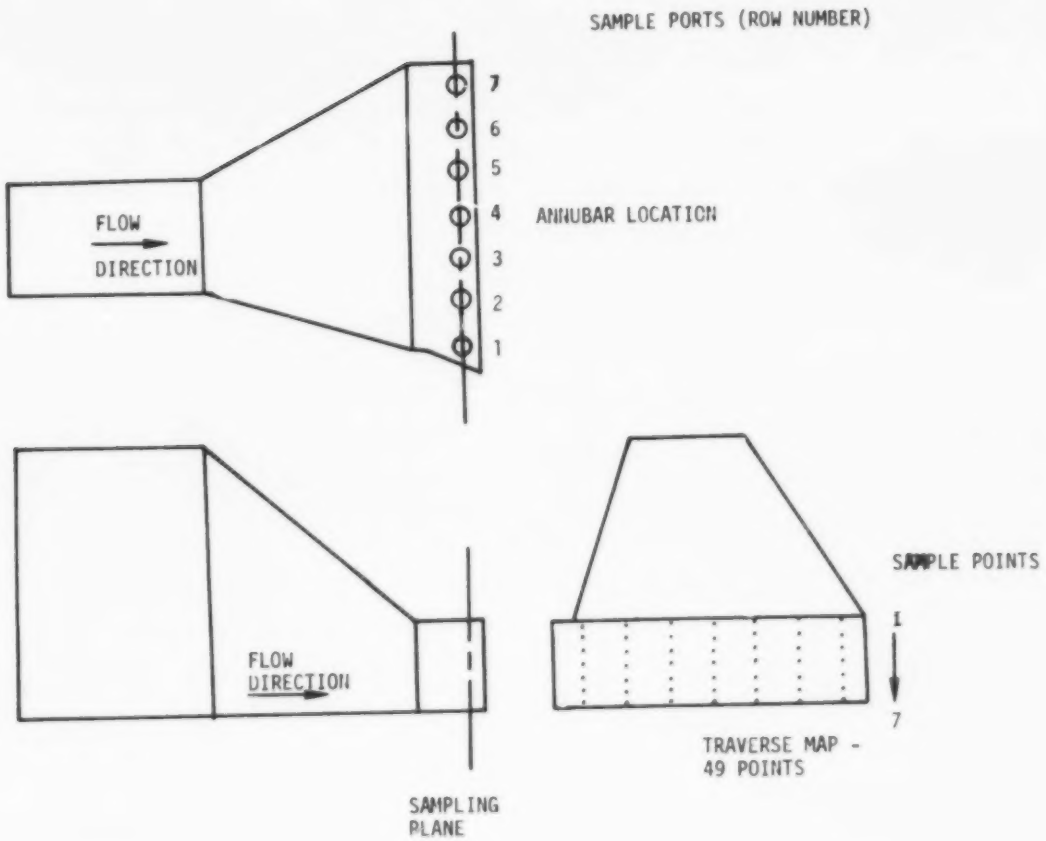


Figure 25. Duct 1 geometry

Sample ports are located in the stack at the 31.4 m level, or about four stack diameters above the inlet. All circular duct testing was performed at this location in the stack.

8.2 TEST CONDUCT

8.2.1 Gas Sampling Hardware

Velocity instrumentation is described in Reference 1. The continuous flow monitors used were Ellison Annubars. Two were used in the first test -- one in duct 1 and one in the stack, as shown in Figure 24. A third was added for the second test and installed in duct 2. Gas analyzers used during the first test included a Beckman NDIR SO_2 analyzer, a Carle thermal conductivity gas chromatograph to measure CO, CO_2, N_2, and O_2 concentrations, and a Thermo Electron chemiluminescent NO_x analyzer. Post test data examination revealed that the SO_2 analyzer had a very slow time response (~20 minutes) which was not evident during the test, and which resulted in incorrect instrument calibration. The result was that the SO_2 data for the first test had to be discarded. Gas sampling for the first test involved point sampling only.

For the second test, a new Carle gas chromatograph was purchased. The new unit had an automatic sampling capability so that it could operate unattended. The older model required manual operation. A pulsed fluorescent SO_2 analyzer was loaned to us for the second test through the courtesy of the Thermo Electron Corporation and their Western Regional office manager, Mr. Jim Nelsen. The NO_x analyzer was the same one used during the first test. The gas chromatograph had its own integrator and digital paper tape printer. Outputs of the SO_2 and NO_x analyzers were fed through a scanner to a digital voltmeter and paper tape printer. Data output intervals varied from ten seconds to one hour, with a nominal ten minute interval. Data reduction was accomplished by use of a digital computer upon completion of field work.

The point sampling probe used during the second test is shown in Figure 26. The sample line was heat traced up to the condenser used to remove water vapor. Four continuous sampling probes were fabricated for the second test. Design is described in Section VII, and shown in

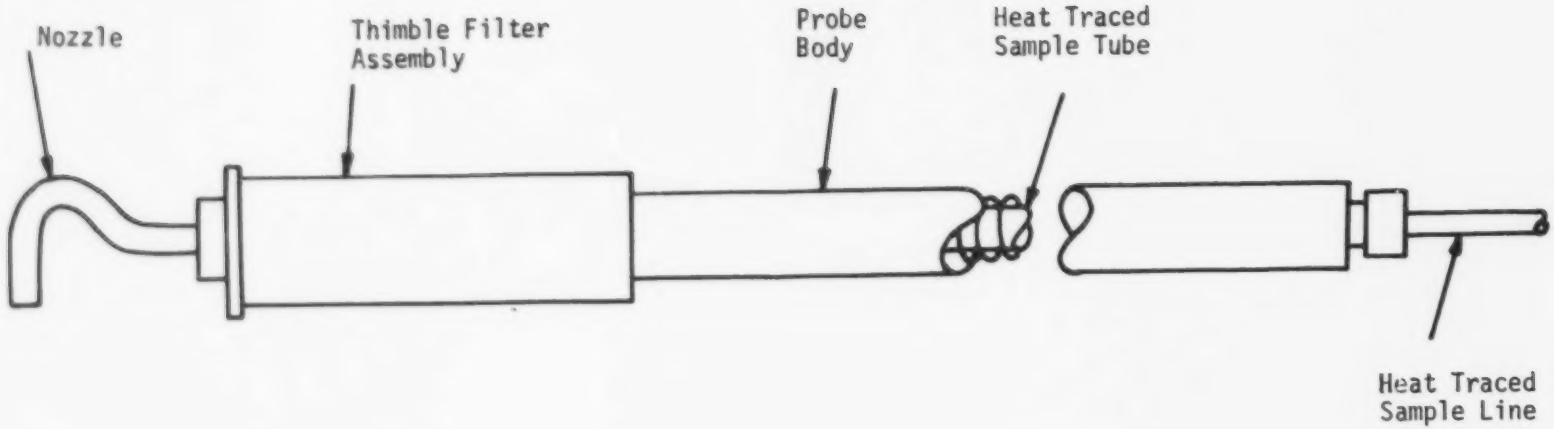


Figure 26. Point sampling probe

Figure 27. The probes were installed at the locations shown in Figure 24. Heat traced lines were used as far as the condenser.

A schematic of the sampling trains is shown in Figure 28. For the second test, two large plexiglas water knockouts (condensers) were fabricated to allow for continuous sampling (one for the duct area and one for the stack). Two pumps from Aerotherm "Super Sniffer" sampling trains were used to provide the desired flow rates. The second pump was used as a backup in case of failure.

8.2.2 Extent of Testing

Sample traverses were performed in duct 1 during the first test to assess stratification levels and provide composition data for flow calculations. In addition, time variation of concentrations at a fixed point was also investigated. Traverses were performed in both ducts 1 and 2 during the second test in addition to the data obtained from the multi-point probes.

A total of four basic plant conditions occurred during the first test, each about equally often. The unit load was held at maximum (~110-120 MW) during the PM hours and at about half that during the AM hours. The scrubber was on about 40% of the time. The unit was down about five days during the test. Full load was maintained during the second test, the variation being from about 100 to 123 MW. The scrubber was on full time except for one five hour period. There was no plant down time during the second test.

8.2.3 Problems

The only notable gas sampling problem during the first test was malfunction of the SO_2 analyzer. The absolute value of the NO_x data for the test seemed unusually high. The analyzer was factory serviced between tests and gave more reasonable data for the second tests. Since the objective during the first test was to determine variations rather than absolute values, the data were considered acceptable for that purpose. Many problems occurred with the velocity measurements during the first test, and these are documented in Reference 1.

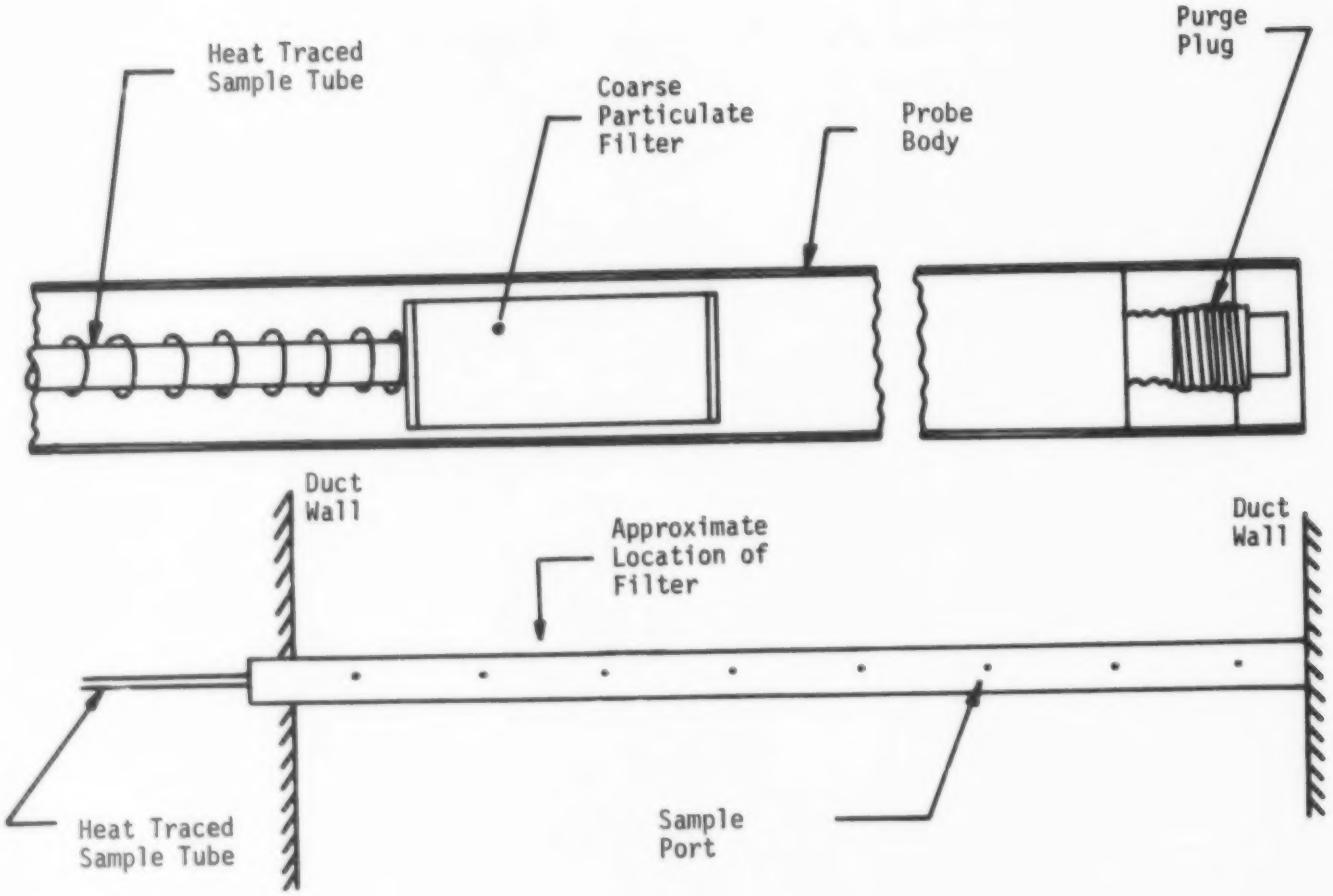
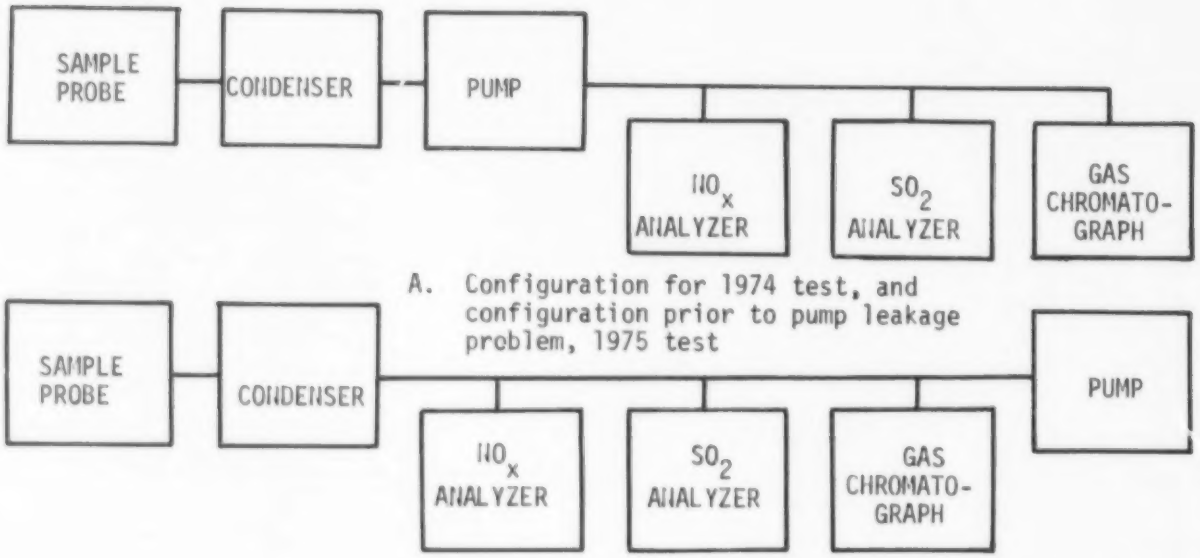


Figure 27. Multi-hole sampling probe for field demonstration



A. Configuration for 1974 test, and configuration prior to pump leakage problem, 1975 test

B. Configuration after pump leakage problem discovered, 1975 test

Figure 28. Schematic of gas sampling train for field demonstrations

The situation reversed for the second test. There were negligible problems with the velocity measurements, but many with the gas sampling work. In retrospect, the primary cause of difficulties was an unfortunately tight test schedule prior to the actual field work. Work on the program came to a virtual standstill during December of 1974 due to the fact that data from various sources were showing lower gas stratification levels than had been expected when the program was conceptualized. It was eventually recognized that although the stratification levels were lower than expected, the problem of obtaining a representative sample was far from trivial. Approval to proceed as originally planned was received early in January. For several reasons, it was decided that the second field demonstration should be conducted at the same place as the first. A severe time constraint became apparent when we were told that the unit would be down for an extended period, starting around the first of March, for annual maintenance. This gave us a month to develop the specialized hardware needed to perform the test, and still have a reasonable length of time to conduct the test. The major difficulties were with procurement: the new gas chromatograph did not arrive in time to be thoroughly checked out in the laboratory. This resulted in much down time for the instrument in the field. The SO_2 analyzer did not arrive until the sixth day of the test. A faulty integrated circuit (replacement cost 59¢) invalidated the output for several subsequent days until the problem could be located through consultation with the factory, and a replacement flown in from Los Angeles.

Other problems during the test included accidental damage to the water knockout units, and accidental ingestion of a large slug of water in the sample line, which rendered the SO_2 analyzer inoperable during the last two days of testing. A significant problem was the development of a leak in the Aerotherm pump midway through the test. The pump was initially placed upstream of the analyzers to provide an acceptably high inlet pressure to the instruments. The backup pump was also found to have too high a leak rate. The pump then had to be placed downstream of the analyzers, as shown in Figure 28. Since the analyzers could not maintain an adequate flow rate due to the low line pressure ahead of the pumps, it was necessary to manually throttle down the pump at each

sampling point to allow the line pressure to rise to an acceptable level. Data were not compromised using this procedure, but it precluded any further continuous sampling. As a result, the only continuous monitoring data obtained were in duct 1, since the data had been taken prior to the leakage problem.

It is felt that the gas sampling data obtained during the second test were adequate to demonstrate the chosen techniques. The problems which occurred simply reduced the amount of data which could be taken.

8.3 FLOW DATA CORRELATION

The gas analyzers were calibrated with bottled calibration gases. This was normally done twice a day, or before and after each traverse. Coal usage per day and coal analysis data were coupled with test composition measurements of CO_2 in the ducts to make independent flow calculations. Coal data were supplied by plant personnel.

8.4 TEST RESULTS

8.4.1 Composition Measurements and Plant Reference Data

Foster-Wheeler specifications for full load nominal bulk composition at the duct sampling planes are as follows:

Gas	% Wet Gas	% Dry Gas
N_2	76.13	80.14
CO_2	13.24	13.94
O_2	5.63	5.92
H_2O	5.00	-

Results of the 1974 sampling measurements in duct 1 are summarized in Table 6 for full load conditions. No full traverses were obtained at half load due to the plant schedule. We did obtain two "half traverses" on different days which were used to calculate nominal composition at half load. Averages for the 1974 test were:

Table 6. MEAN VALUES AND STRATIFICATION LEVELS FOR 1974 FIELD DEMONSTRATION

GAS	DUCT	RUN	MEAN VALUES		STRATIFICATION LEVEL, 2σ, % of Mean Value
			Spatial	Flow Proportional	
CO_2 % of dry gas	1	-	15.84	15.85	±7.4
NO_x, ppm	1	1	734	735	±7.0
		2	800	805	±16.0
O_2, % of dry gas	1	-	4.32	4.30	±23.2

	Full Load		Half Load	
Gas	% Wet Gas	% Dry Gas	% Wet Gas	% Dry Gas
N_2	76.65	79.85	79.96	82.43
CO_2	15.22	15.85	8.81	9.08
O_2	4.13	4.30	8.23	8.49
H_2O	4.00	-	3.00	-

Results for the 1975 test are summarized in Table 7. Recall that the unit was only at full load during the 1975 test. Bulk composition for the 1975 test was as follows:

Gas	% Wet Gas	% Dry Gas
N_2	75.40	80.39
CO_2	12.99	13.85
O_2	5.40	5.76
H_2O	6.21	-

Water vapor content was calculated from ambient humidity and plant measurements of water content in the coal. In 1974 testing at half load, coal usage was half that at full load while the total flowrate was about 70% of the full load flow rate. Thus quite a bit more excess air was used at half load than at full load. During the 1975 test the unit was always at full load and the gas composition was very close to the nominal specifications.

Good correlation was obtained for total mass flow as well as for gas composition. Total flow measurements from the Annubars were compared to flow calculations based on daily coal usage and average CO_2 concentrations in the ducts. Results are presented in Tables 8 and 9, which are taken from Reference 1. Table 8 shows the calculation technique and results for two days of testing in 1974. Table 9 shows similar results for 1975 testing. The "insufficient data" designation in Table 9 means that the pressure transducer used to monitor the duct 2 Annubar was being used for other purposes on the days noted. Both Tables 8 and 9 show total flow correlations on the order of 2% between test and reference measurements.

Table 7. MEAN VALUES AND STRATIFICATION LEVELS FOR 1975 FIELD DEMONSTRATION

GAS	DUCT	RUN	MEAN VALUES		STRATIFICATION LEVEL, 2σ, % of Mean Value
			Spatial	Flow Proportional	
CO_2, % of dry gas	1	-	13.16	13.14	±9.0
	2	-	14.54	14.55	±9.0
SO_2, ppm	1	-	277	278	±20.6
	2	-	344	345	±19.7
NO_x,	1	1	373	373	±8.6
		2	479	480	±6.9
	2	1	449	451	±14.3
		2	416	416	±13.5
O_2, % of dry gas	1	-	5.79	5.76	±13.4
	2	-	5.75	5.75	±8.6

Table 8. COMPUTATION OF TOTAL FLOW FROM COAL ANALYSIS AND MEASURED CO_2 CONCENTRATION, 1974

Date	Coal Used kg	Carbon Used kg	Carbon Used gm-moles	Average CO_2 %	Total Moles of Dry Gas	Total Moles of Wet Gas
10-2	3,251,380	2,752,618	4.729×10^7	11.89	3.977×10^8	4.122×10^8
10-3	3,571,480	3,023,614	5.195×10^7	12.74	4.078×10^8	4.226×10^8

Date	Annubar Average Flow Rate, SCMS	Annubar Total Flow SCM	Total Wet Gas Volume, SCM	Difference %
10-2	104.5	9.026×10^6	9.234×10^6	+ 2.3
10-3	109.4	9.451×10^6	9.466×10^6	+ 1.6

Table 9. AVERAGE DAILY FLOW THROUGH DUCTS, 1975

Date	Average Flow And Standard Deviation, Test SCM/SEC			Average Flow In Ducts From Plant Data SCM/SEC
	Duct 1	Duct 2	Total	
2-15	63.4 ± 1.7	X	X	132.0
2-16	63.5 ± 2.8	X	X	132.6
2-17	64.7 ± 2.3	64.6 ± 1.9	129.3	134.3
2-18	67.3 ± 2.2	64.5 ± 2.4	131.8	135.1
2-19	65.8 ± 2.3	65.2 ± 3.0	131.0	132.8
2-20	65.3 ± 1.6	66.7 ± 2.9	132.0	134.7
2-21	65.1 ± 0.9	64.3 ± 3.9	129.4	133.7
2-22	63.2 ± 2.6	67.3 ± 8.2	130.5	132.9
2-23	64.3 ± 5.2	X	X	128.1
2-24	60.1 ± 8.5	67.3 ± 3.0	127.4	130.6
2-25	62.5 ± 1.7	67.2 ± 0.9	129.7	130.1
2-26	62.7 ± 1.8	66.7 ± 2.1	129.4	132.7
2-27	60.8 ± 2.1	X	X	130.2
2-28	60.3 ± 1.6	X	X	126.3
Ave	63.5	66.0	129.5	131.9

X Indicates insufficient data

8.4.2 Assessment of Stratification

Stratification levels for the various gases are shown in Tables 6 and 7. They are generally of the same order of magnitude as in the Exxon data, with the exception of relatively low O_2 stratification. In all cases, excellent agreement was obtained between spatial and flow proportional averages, further strengthening the validity of spatial gas sampling.

Concentration maps are presented in Figures 29-42. The only general comment to be made is that stratification is generally greater in the direction parallel to the long sides of the duct, as was the case for the Exxon data. This may be in part due to the fact that the rotary air preheaters just upstream of the test area have a vertical interface with the ducting, so any leakage at that point would tend to result in horizontal rather than vertical stratification. Thus results are as expected if we assume some leakage at the preheater area.

8.4.3 Technique Evaluation

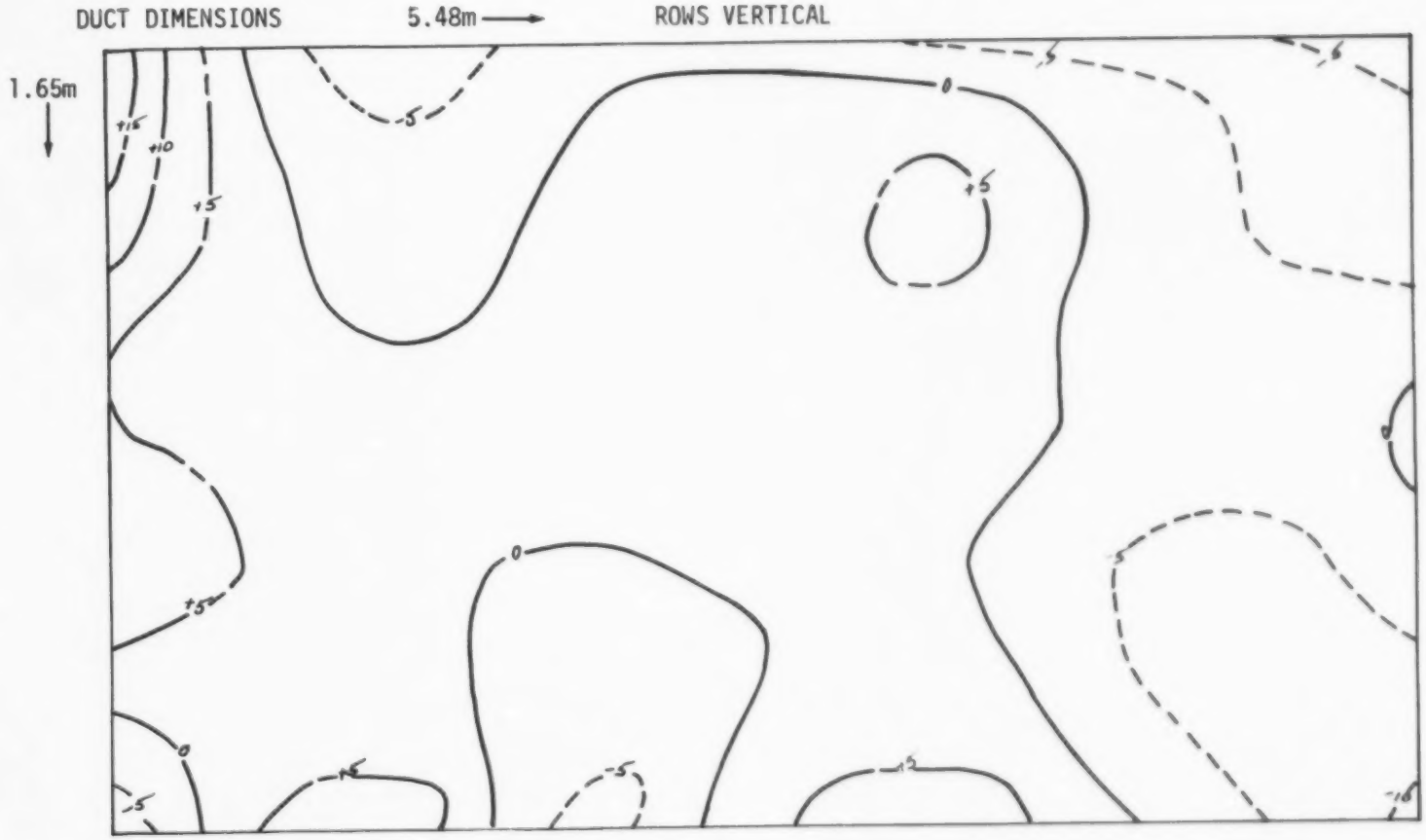
Row Average analyses are presented in Figures 43-45. In Figure 43, the CO_2 curves show the most uniform row averages while the SO_2 data show the least desirable results. The NO_x data in Figure 44 show good results for three of the four runs, and fairly good agreement was attained for all gases in Figure 45.

Due to the problems described in Section 8.2.3, the only multi-hole probe sampling data were obtained in duct 1. Results for a twelve hour sampling period are shown in Table 10. The average CO_2 and O_2 concentrations for the multi-hole probe agree with the traverse averages for duct 1 in Table 7 within 3% and 2%, respectively. The row location was 35.7% of the duct width from the left wall. As can be seen in Figure 43, this location showed good agreement between row averages calculated from traverse data and the mean flow proportional concentration.

Evaluation of the Walden CO_2 tracer method is shown in Table 11. Correlation was about the same as for the Exxon data.

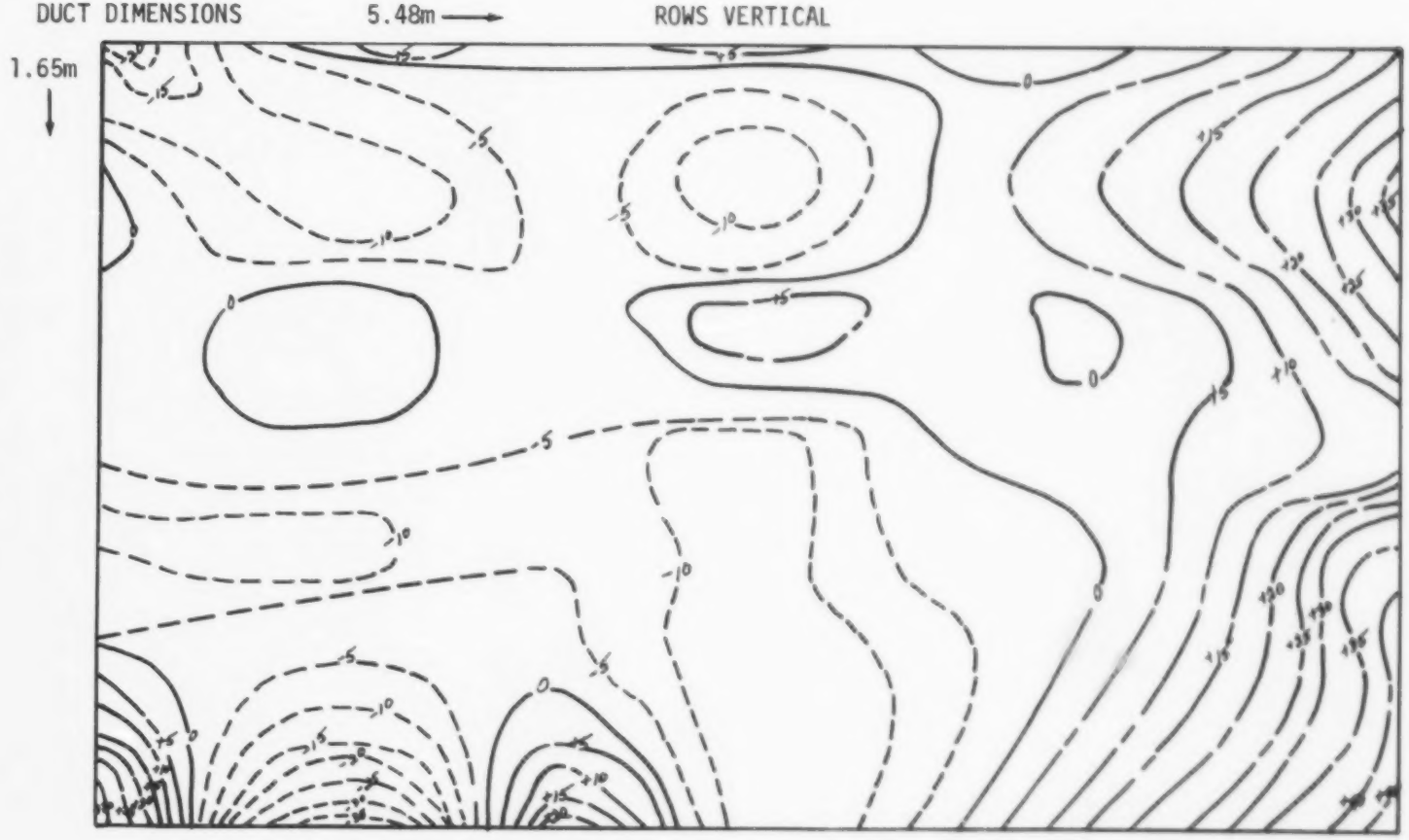
8.4.4 Assessment of Temporal Variations

Short term and overnight point sampling data were taken to determine changes in concentration at a point as a function of time. Data in



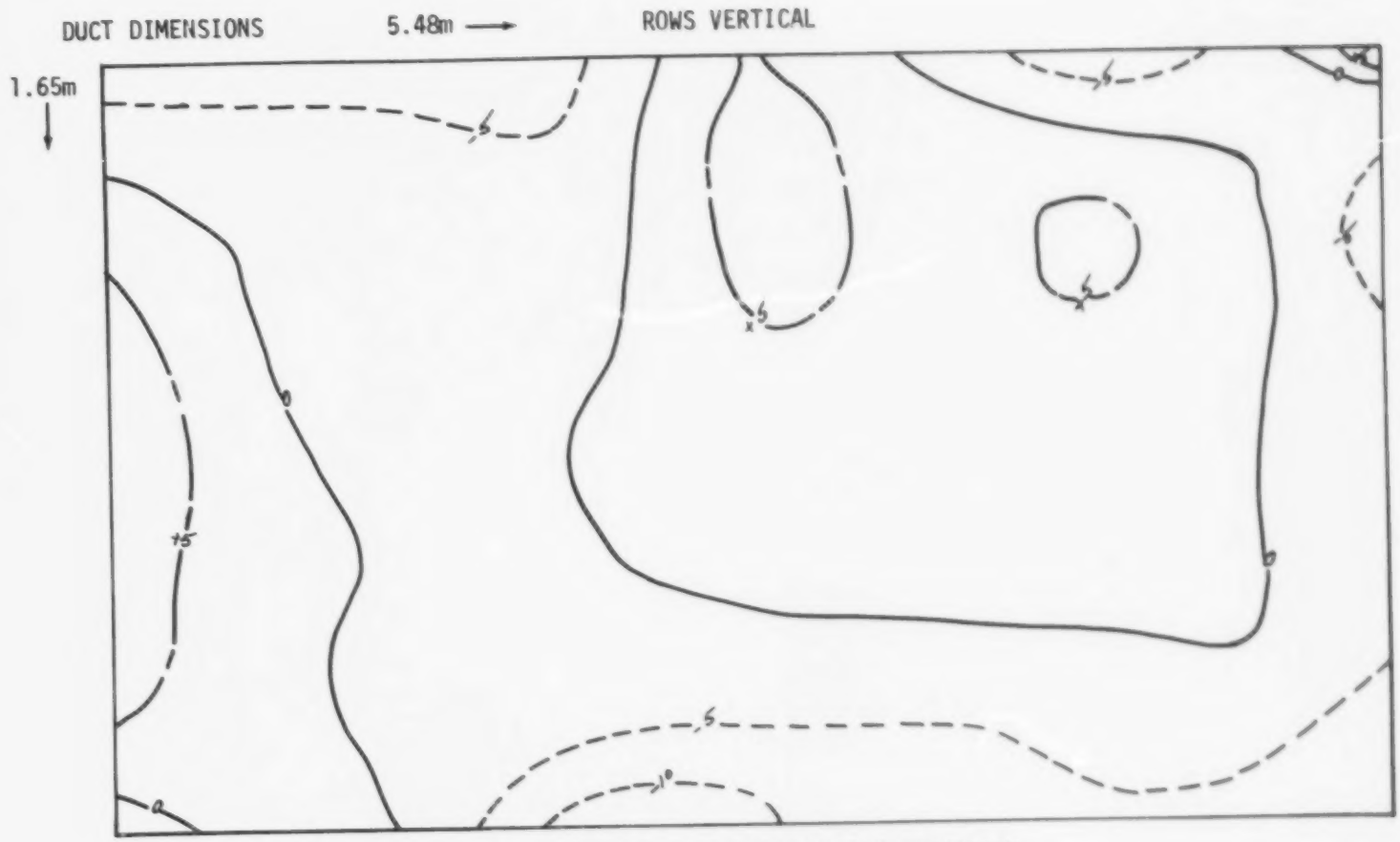
PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION
MEASURED MEAN CONCENTRATION = 15.85% OF DRY GAS

Figure 29. Normalized CO_2 concentration distribution-duct 1, 1974



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION
MEASURED MEAN CONCENTRATION = 4.30% OF DRY GAS

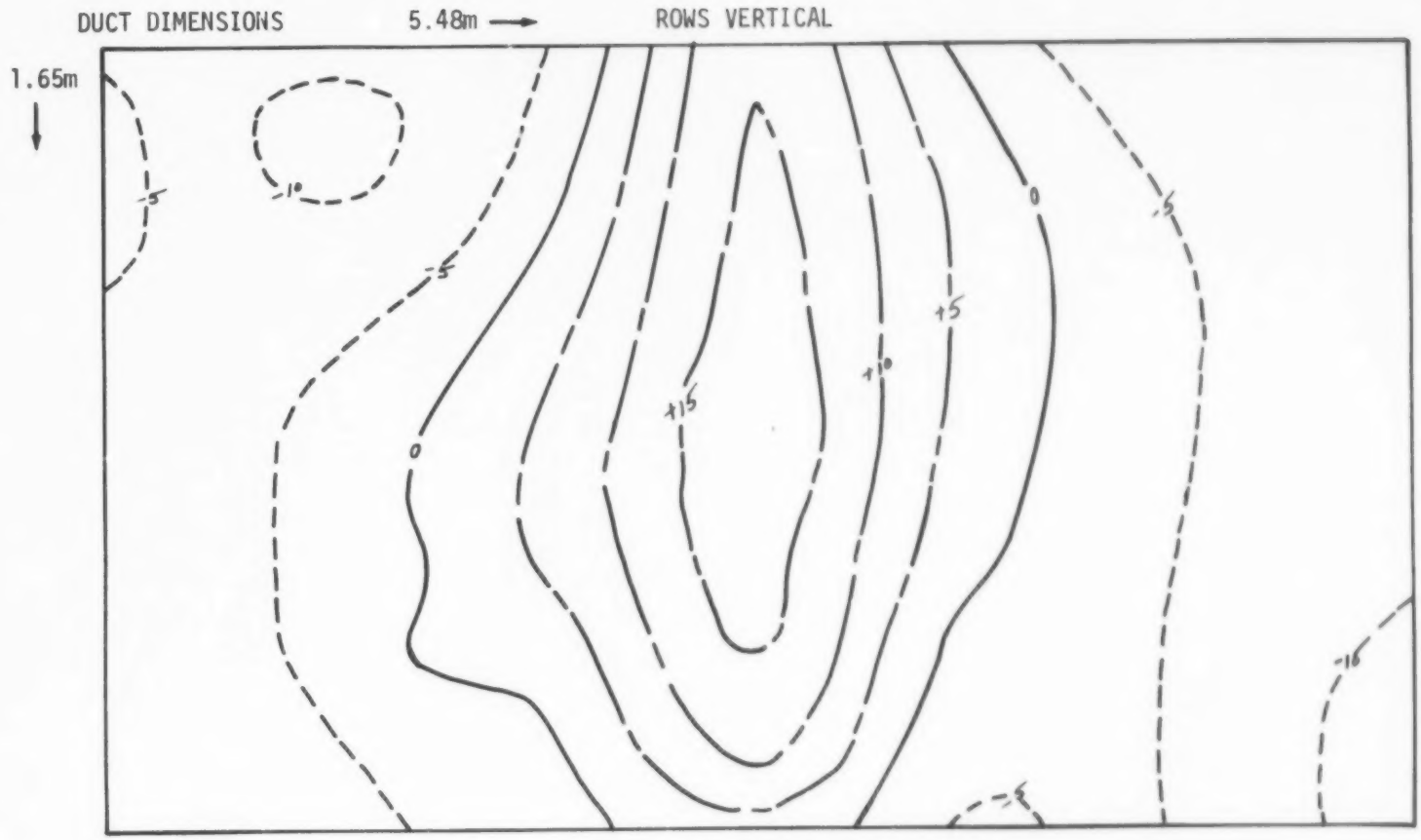
Figure 30. Nromalized O_2 concentration distribution--duct 1, 1974



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 735 PPM

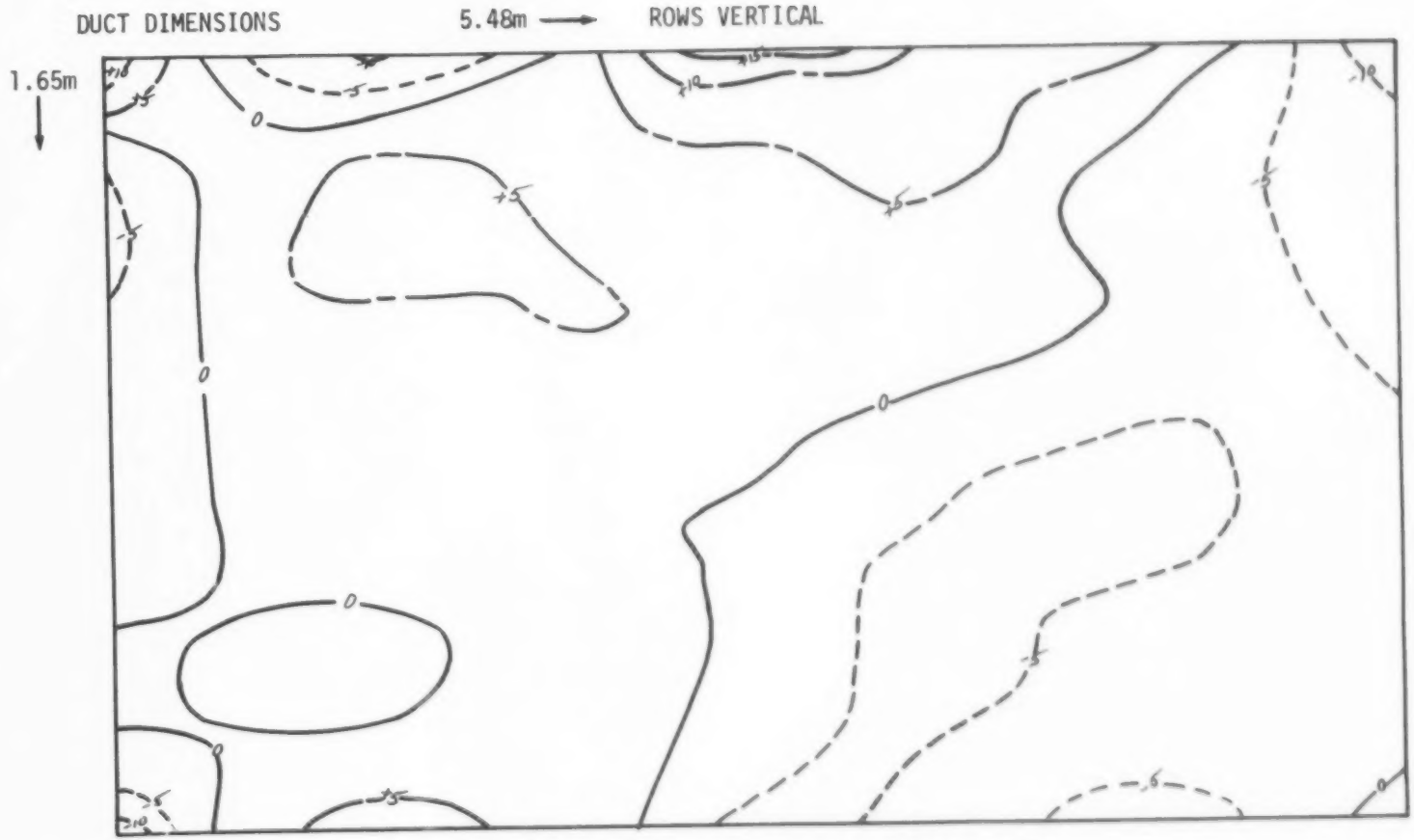
Figure 31. Normalized NO_x concentration distribution--duct 1, 1974, run 1



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 805 PPM

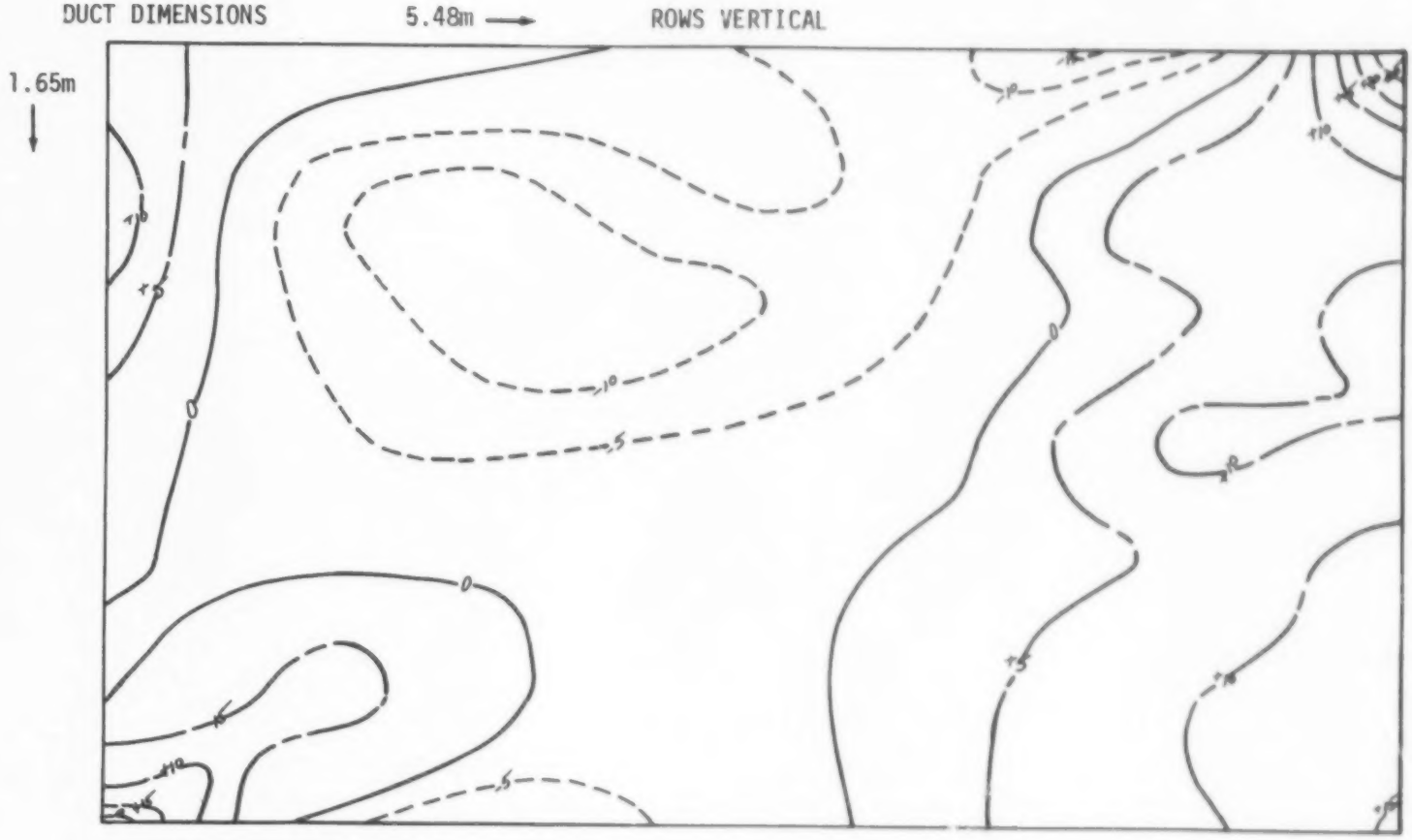
Figure 32. Normalized NO_x concentration distribution--duct 2, 1974, run 2



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 13.14% OF DRY GAS

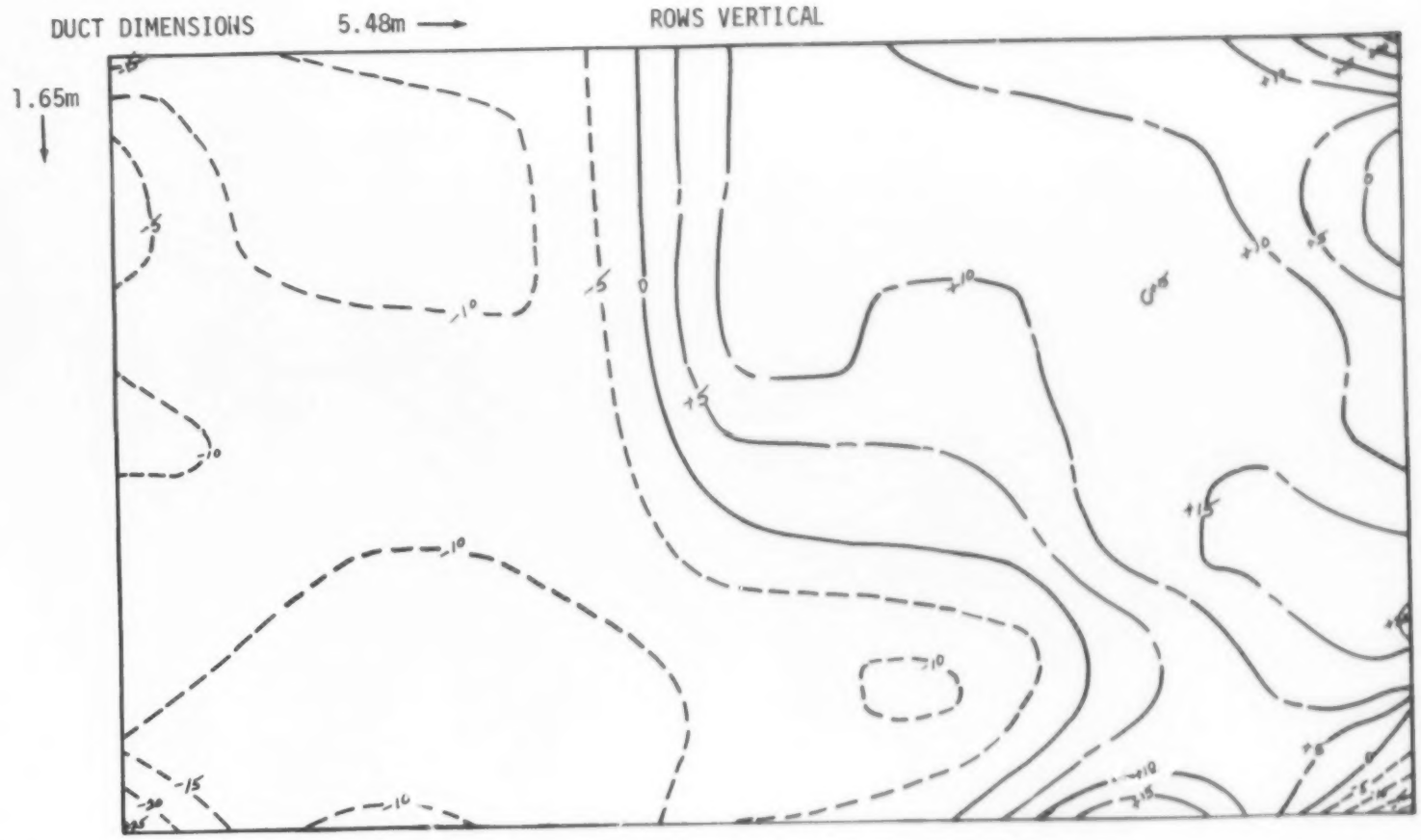
Figure 33. Normalized CO_2 concentration distribution-duct 1, 1975



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION MEASURED

MEAN CONCENTRATION = 5.76% OF DRY GAS

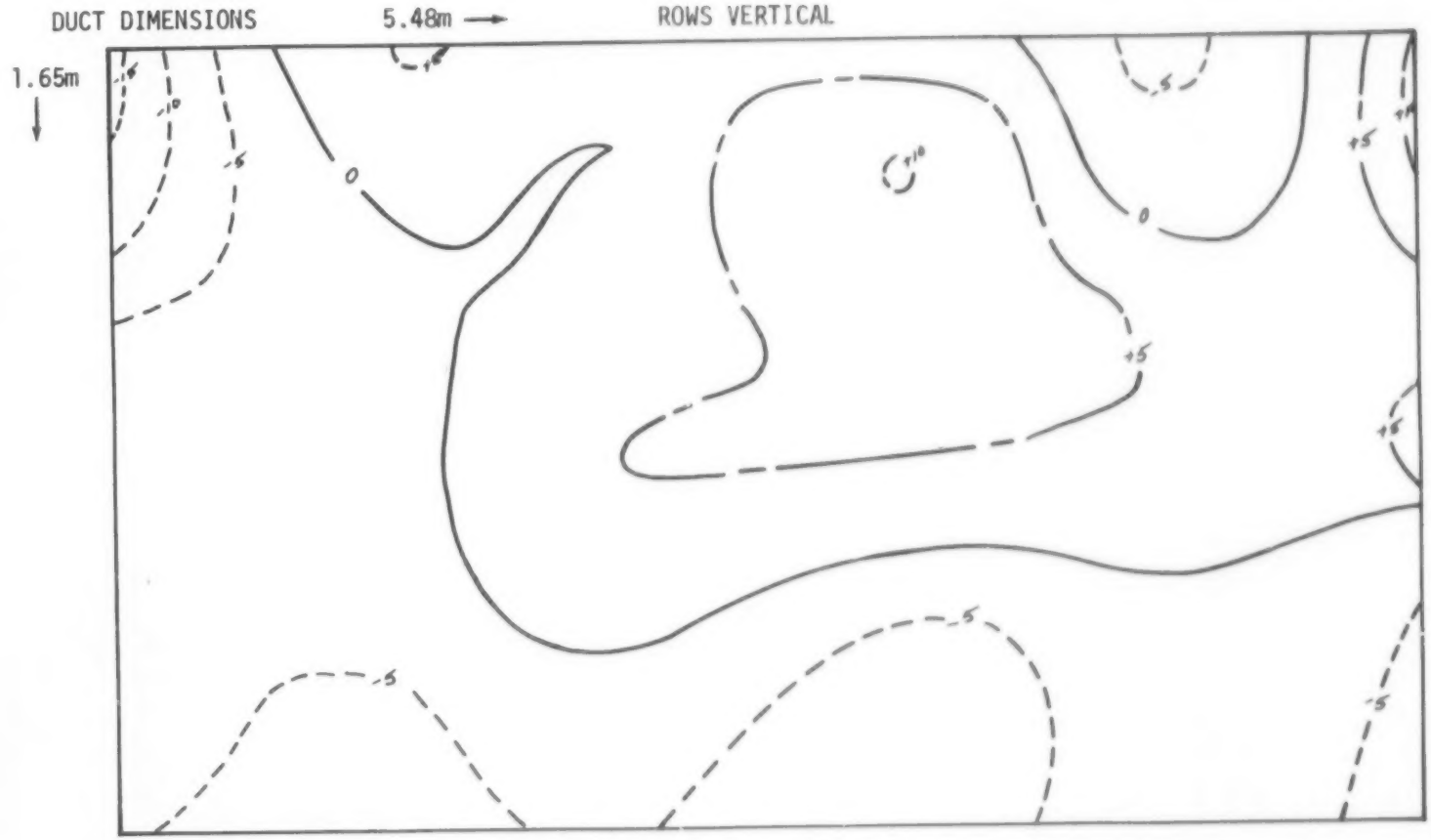
Figure 34. Normalized O_2 concentration distribution--duct 1, 1975



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 278 PPM

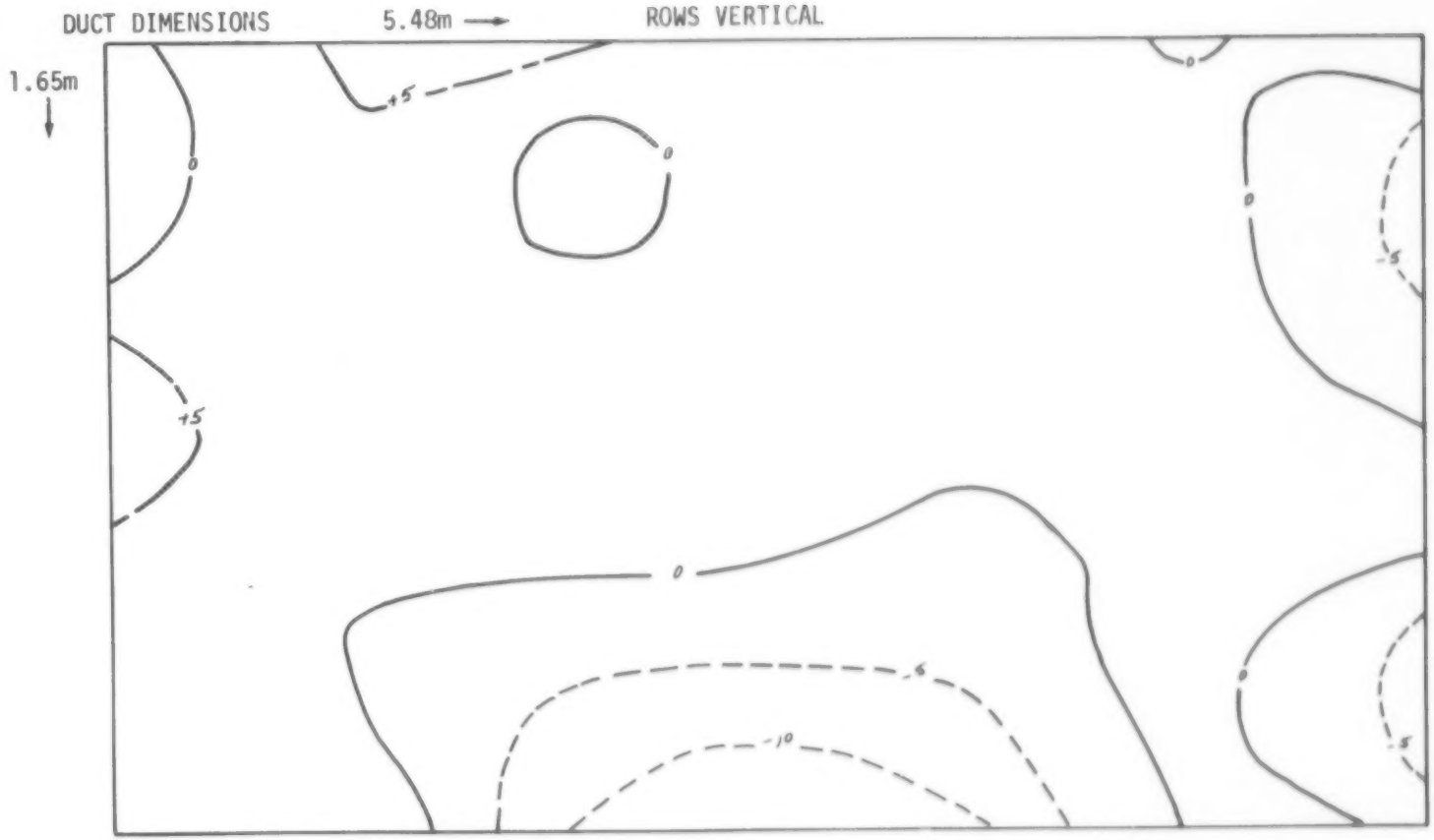
Figure 35. Normalized SO_2 concentration distribution--duct 1, 1975



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 373 PPM

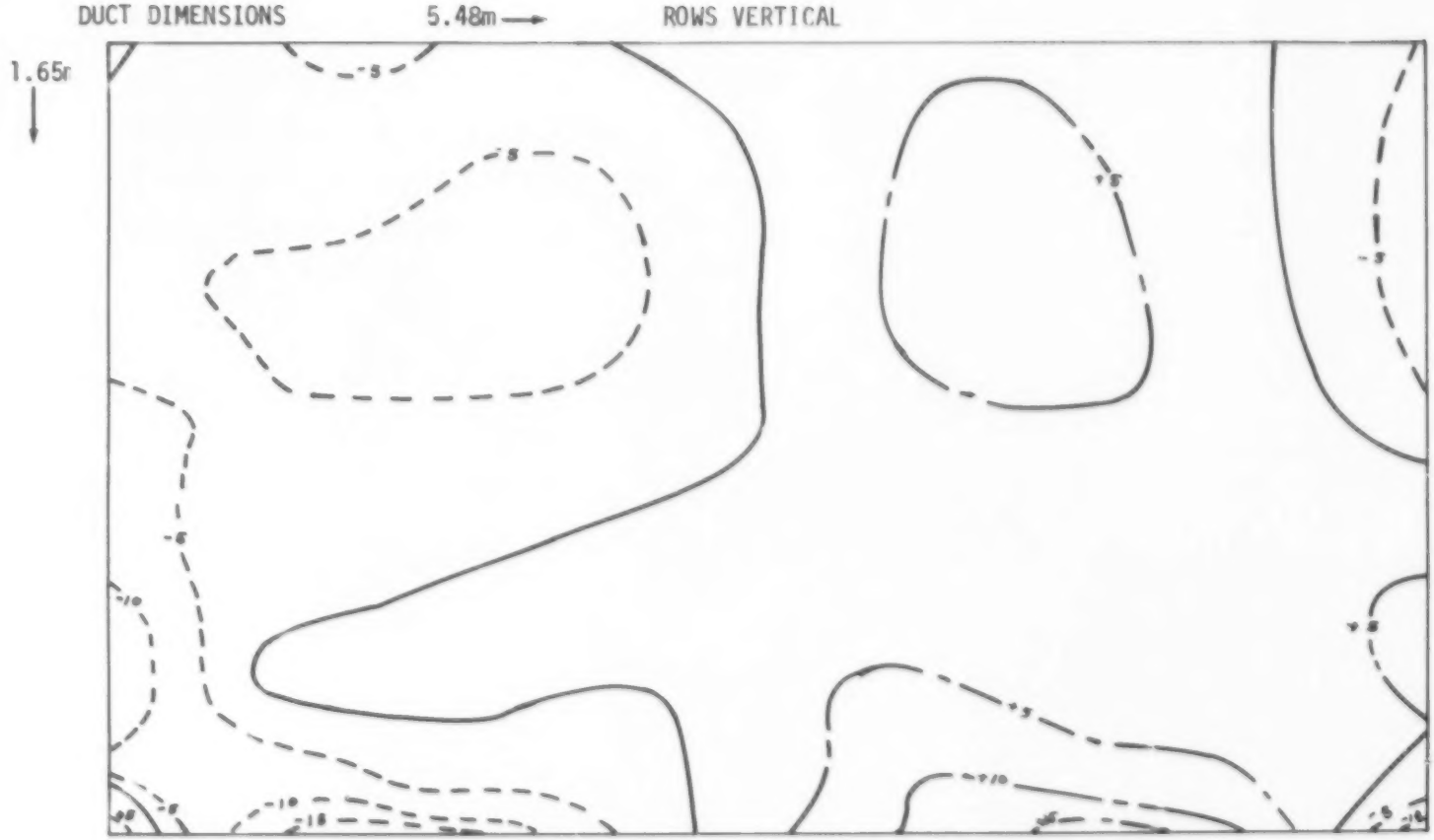
Figure 36. Normalized NO_x concentration distribution--duct 1, 1975, run 1



PROFILES ARE VARIATION IN %5 INCREMENTS FROM MEAN CONCENTRATION

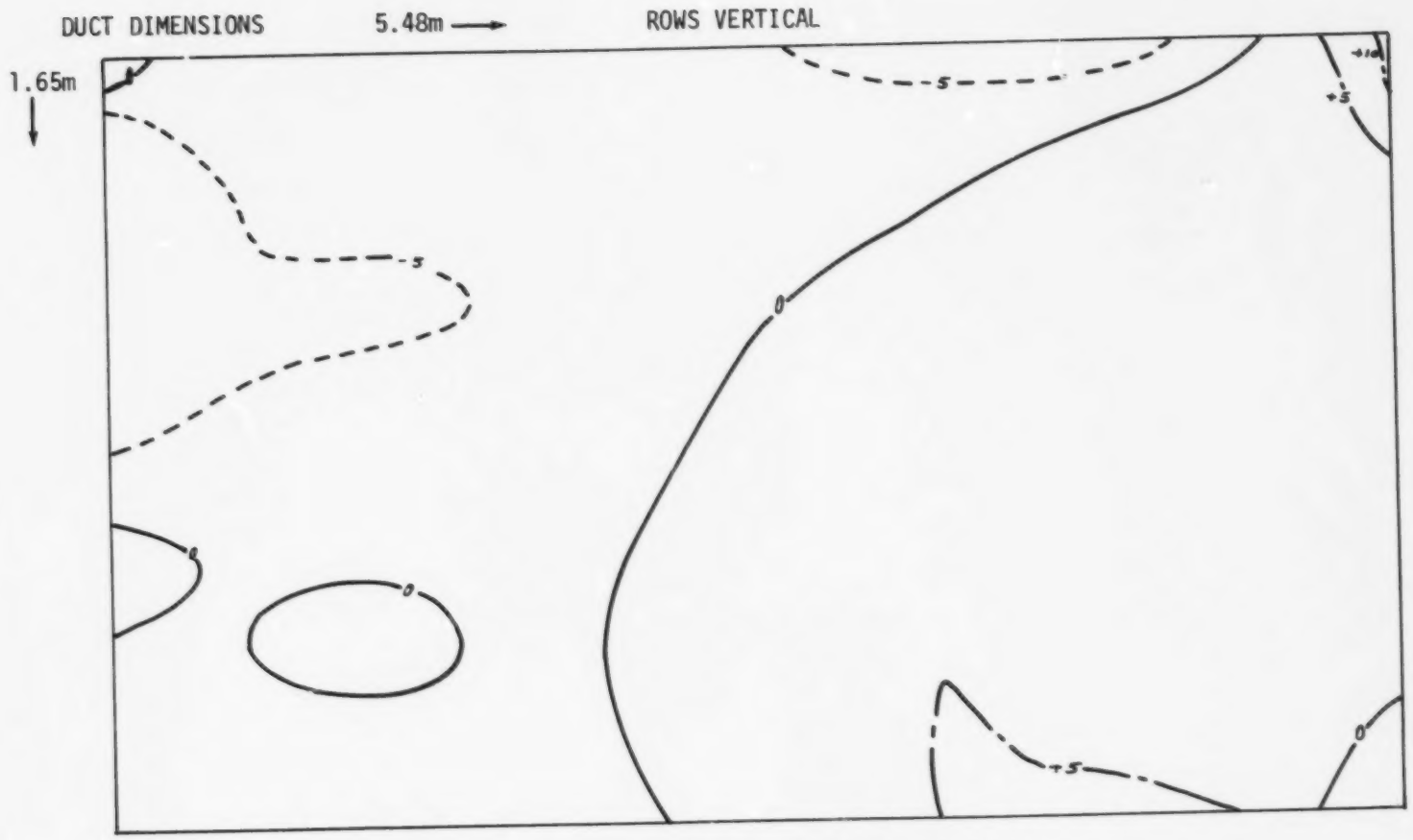
MEASURED MEAN CONCENTRATION = 480 PPM

Figure 37. Normalized NO_x concentration distribution--duct 1, 1975, run 2



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION
MEASURED MEAN CONCENTRATION = 14.55% OF DRY GAS

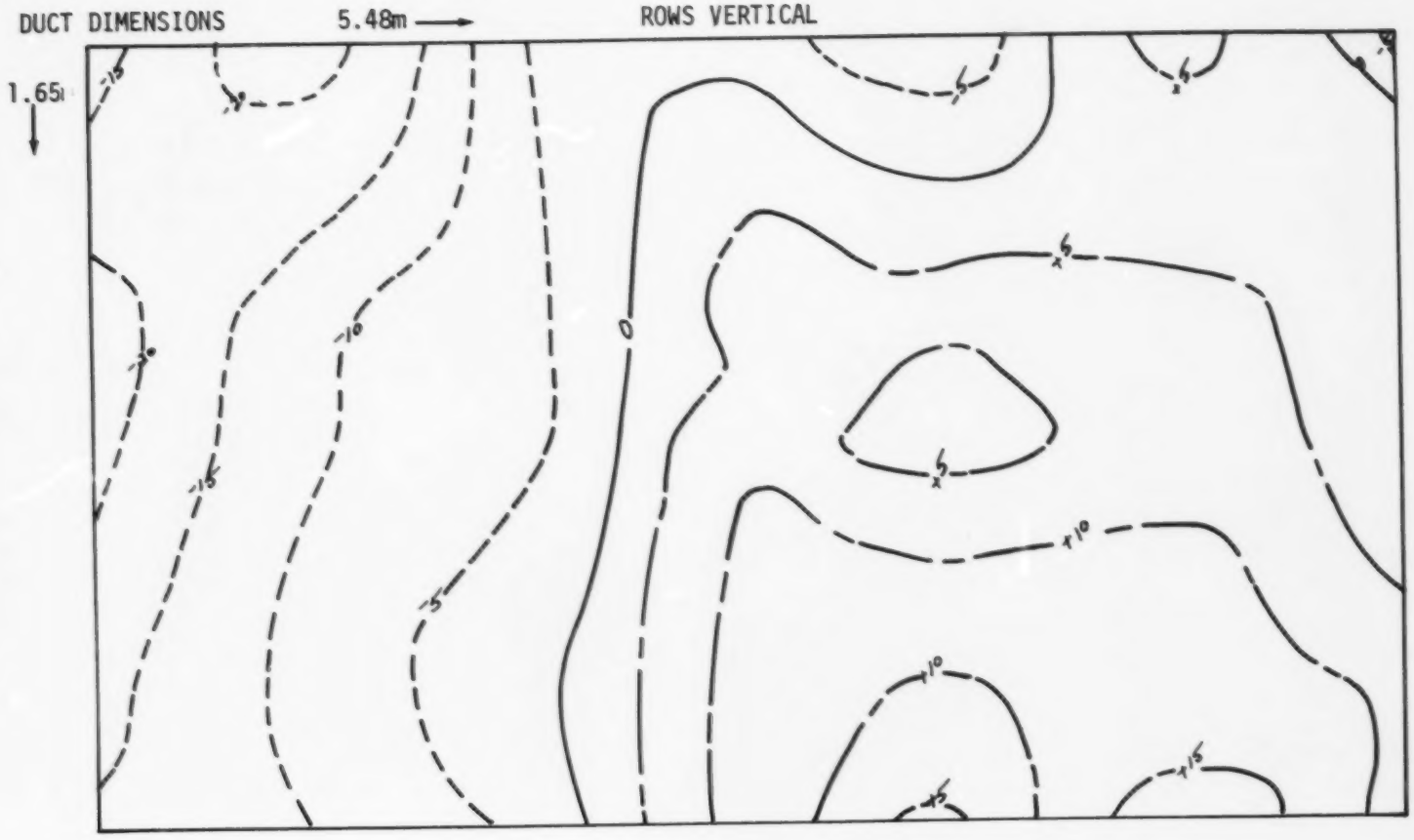
Figure 38. Normalized CO_2 concentration distribution--duct 2, 1975



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 5.75% OF DRY GAS

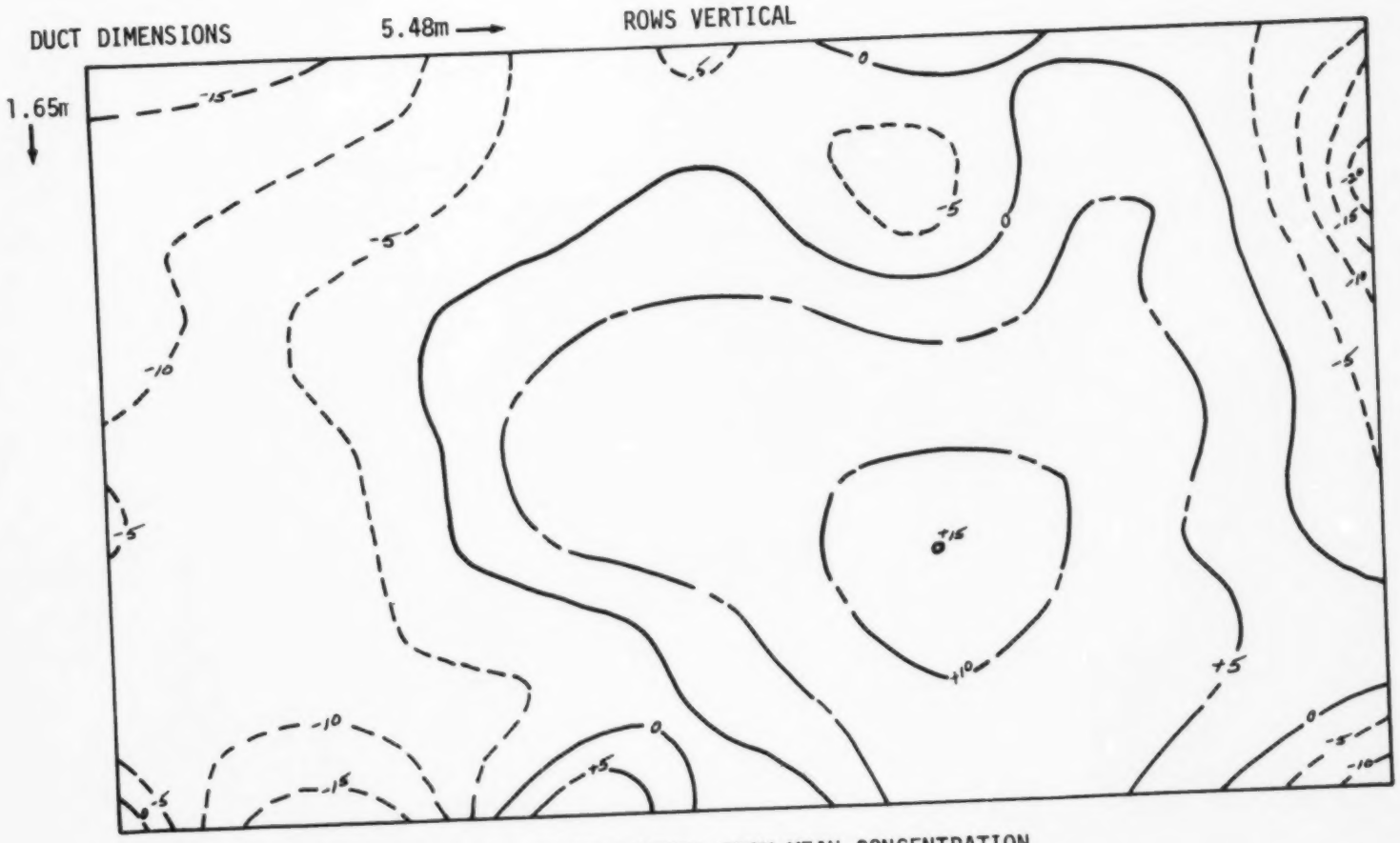
Figure 39. Normalized O_2 concentration distribution--duct 2, 1975



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 345 PPM

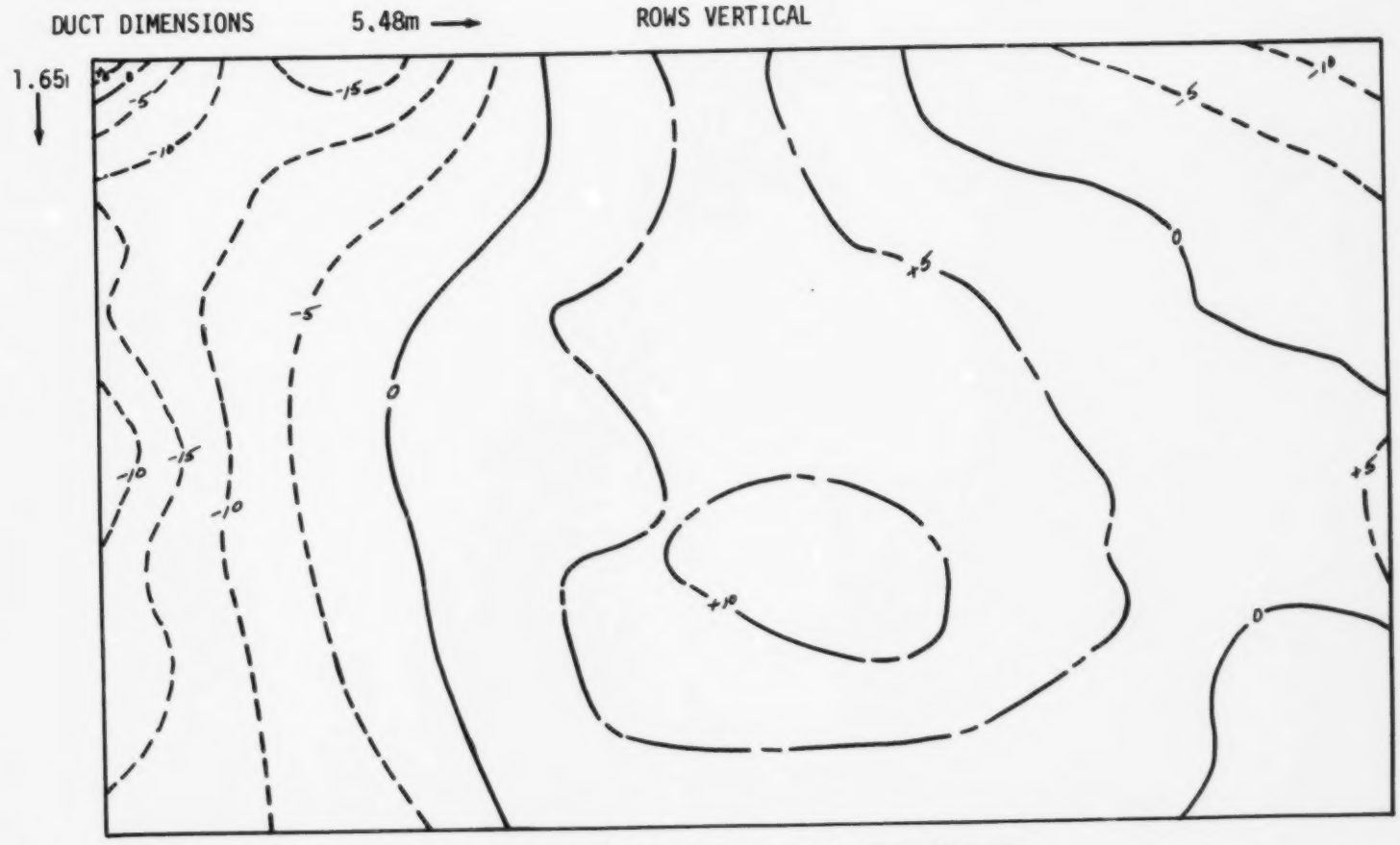
Figure 40. Normalized SO_2 concentration distribution--duct 2, 1975



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 451 PPM

Figure 41. Normalized NO_x concentration distribution--duct 2, 1975, run 1



PROFILES ARE VARIATION IN 5% INCREMENTS FROM MEAN CONCENTRATION

MEASURED MEAN CONCENTRATION = 416 PPM

Figure 42. Normalized NO_x concentration distribution--duct 2, 1975, run 2

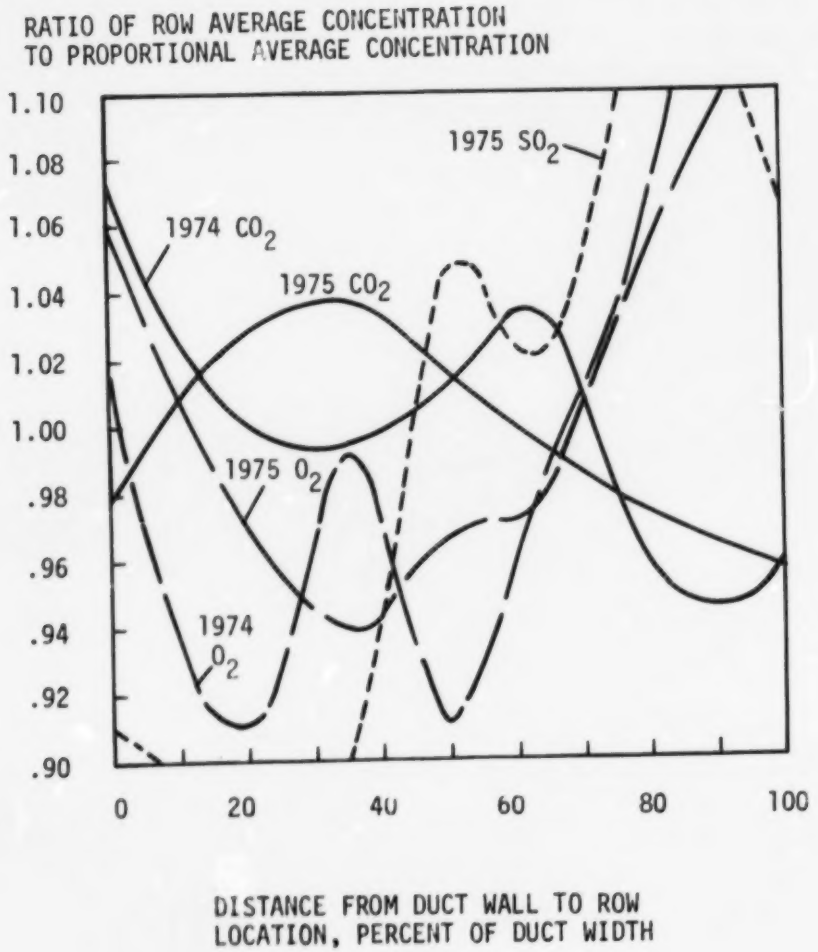


Figure 43. Row average analysis for CO_2, O_2, and SO_2 concentration maps--field demonstrations, duct 1

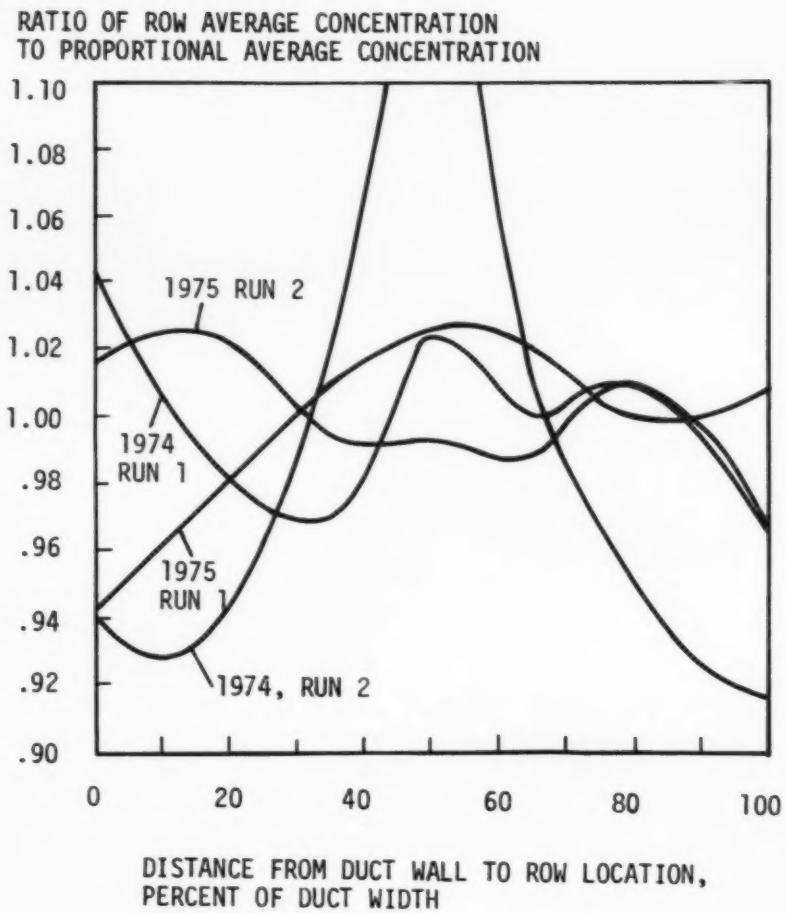


Figure 44. Row average analysis for NO_x concentration maps--field demonstrations, duct 1

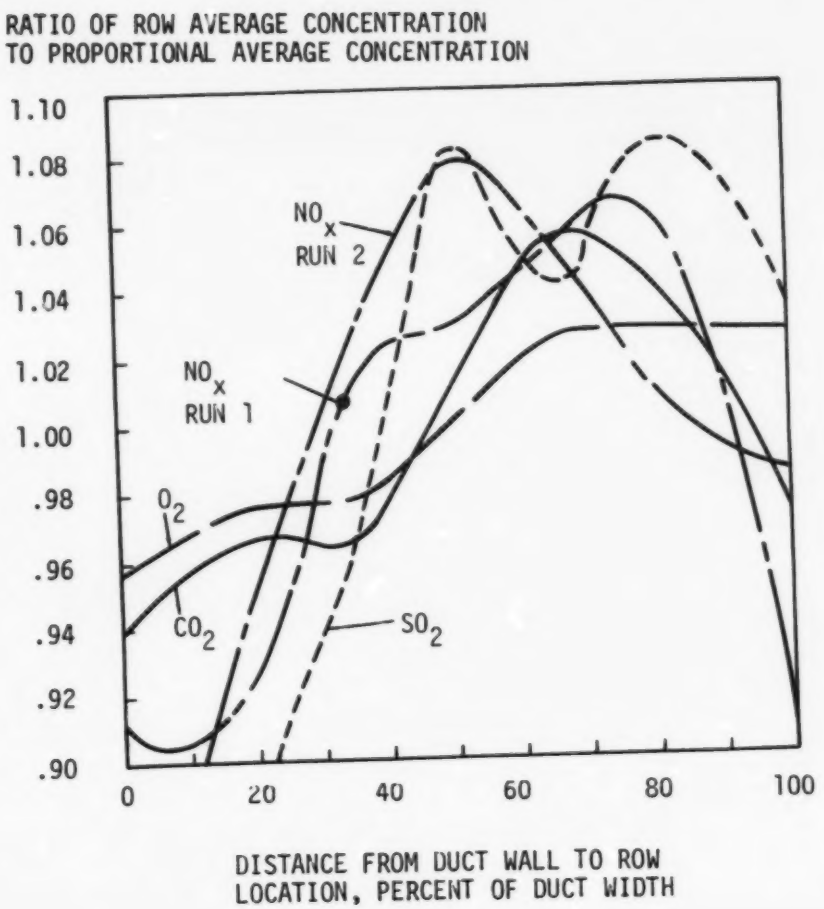


Figure 45. Row average analysis for CO_2, O_2, SO_2, and NO_x concentration maps--field demonstrations, duct 2

Table 10. MULTI-HOLE SAMPLING PROBE OVERNIGHT SAMPLING RESULTS, 1975

Start: 7 PM, 2-19

End: 7:10 AM, 2-20

Number of data points: 26 (taken on the hour and ten minutes after the hour)

GAS	MEAN VALUE, % OF DRY GAS	2σ DEVIATION, % OF MEAN VALUE
CO_2	13.55	±17.8
O_2	5.88	±4.2
N_2	80.57	±2.8

Probe position: Duct 1, Port 5

Table 11. CO_2 TRACER METHOD ANALYSIS OF FIELD DEMONSTRATION DATA

	2σ, % OF MEAN VALUE
1974 TEST Duct 1 NO_x/CO_2	$\pm$8.9
1975 TEST Duct 1 NO_x/CO_2 SO_2/CO_2	$\pm$23.1 $\pm$8.8
Duct 2 NO_x/CO_2 SO_2/CO_2	$\pm$12.1 $\pm$15.7

Explanation of tabular values:

2σ = $\pm$8.9% of mean value for NO_x/CO_2 ratio means that there is a 95.4% probability that the ratio of the NO_x reading to the CO_2 reading at any point in the duct will agree with the average NO_x/CO_2 ratio within $\pm$8.9%.

Table 12 showed that at a given point, concentrations were very constant for periods on the order of half an hour. Variations between points were clearly much larger. Overnight data, as shown in Table 13, showed significantly greater variations. Note that the standard deviation of 23 ppm is larger than most of the differences between successive readings. This demonstrates a "time constant" for variations that is more on the order of hours than minutes.

8.5 SUMMARY OF RESULTS

Average concentration determinations from gas sample traverses agreed well with nominal plant specifications. Correlation of total mass emission measurements with plant coal usage data was excellent. This agrees with the statement made in Section IV that better accuracy should be expected for total mass emission than for mass emission of any single gas. The Row Average data suggest possible measurement accuracies for individual species of about $\pm$4%, although the one twelve hour period of continuous sampling showed 2-3% agreement. It would appear likely that better correlation will be obtained for long sampling intervals rather than short ones. The rate of concentration variations at a single point suggests that sample traverses should be performed in as short a time as possible to avoid errors due to temporal variation. A traverse time of two hours or less would appear reasonable for this power plant. The CO_2 tracer technique showed fairly poor results, as was the case with the Exxon data. The test result which should have the greatest implication for future work was the continued excellent agreement between spatial and flow proportional mean values. The average stratification level, 2σ, was $\pm$13%, which is lower than the levels of the Exxon and TVA data, but still too high to justify single point sampling.

Table 12. SHORT TERM STATIONARY POINT GAS SAMPLE DATA, 1974, DUCT 1

AVERAGE LOAD, MW	TIME DURATION, MINUTES	READINGS	POSITION, ROW-POINT	GAS	MEAN VALUE, % OF DRY GAS	2σ, % OF MEAN VALUE
109	26	7	2-4	N_2	79.67	±.22
				O_2	5.63	±.24
				CO_2	14.67	±.24
108	25	6	3-4	N_2	79.77	±1.06
				O_2	5.61	±.86
				CO_2	14.63	±.38
100	32	8	6-4	N_2	78.92	±.30
				O_2	5.29	±.38
				CO_2	15.80	±.14
88	26	6	7-4	N_2	77.67	±.38
				O_2	7.27	±.38
				CO_2	15.05	±.30
80	15	5	5-4	N_2	77.43	±.44
				O_2	7.09	±.38
				CO_2	15.43	±.20

Table 13. OVERNIGHT NO_x GAS SAMPLE DATA, 1974

Date	Time	Load MW	NO_x Concentration, PPM
10-4	19:50	53	261
	20:50	54	308
	21:50	52	314
	23:40	53	282
10-5	0:30	53	273
	1:00	53	268
	3:00	55	250
	4:00	54	256
	5:00	54	234
	6:00	54	243
	7:00	55	236
	8:00	55	252
	9:00	53	273
	9:30	54	279

AVE = 266 $\pm$ 23

2σ = $\pm$17.6% of mean value

SECTION IX
DISCUSSION OF RESULTS

9.1 GENERAL

Current sampling techniques in large ducts tend to fall into two extremes: careful manual sampling is done according to Federal Register Method 1 (Reference 4), and often involves in excess of forty traverse points. Continuous monitoring is more often done at a single point for reasons of cost and simplicity. Data examined during this program have shown stratification levels on the order of 10-15% and poor temporal repeatability. On this basis, we have concluded that single point sampling is generally not acceptable if good accuracy is desired. At the other extreme, we recognize the impracticability of large sampling arrays. Thus, our purpose has been to find an economically feasible and technically acceptable (from the standpoint of accuracy) middle ground, both for measurement of total volumetric flow and gaseous emissions.

The accurate measurement of constituent gaseous emissions in process streams is inherently more difficult than the measurement of total gaseous emissions simply because the latter is required in order to determine the former. Methods to continuously monitor total gaseous emissions were developed and evaluated during the first phase of the program. Results documented in Reference 1 showed that good accuracy could be attained through proper use of as few as one flow sensor in large ducts with very undeveloped flow profiles. We therefore approached the gas composition measurement phase of the program with the attitude that the simplest hardware system for continous monitoring would probabily involve independent flow and composition subsystems. On this basis, we were extremely pleased to discover the excellent correlation between spatial and flow proportional mean concentrations. This agreement justified the separation of flow and composition measurements on the basis of accuracy.

There is an intuitive relationship between gas stratification levels and the complexity of hardware required to obtain a representative sample.

One program objective was to establish a standard technique to specify the magnitude of stratification in a usable manner. The most obvious parameter for this purpose would be the standard deviation for a normal distribution (Reference 3, Chapters 8-9), since this parameter is the most commonly used in the evaluation of propagation of errors. The key question was whether concentration data followed a normal distribution in the sampling plane. Data from several runs showed a reasonably normal distribution, so the validity of the approach was accepted. It is suggested that consideration be given to adopting the "2σ" definition of stratification levels for purposes of standardization.

9.2 METHOD DEVELOPMENT AND EVALUATION

The correlation between spatial and flow proportional mean values was the basis for method development work. The primary proposed method is the Row Average technique developed originally for velocity measurement. This technique showed reasonable results for gas sampling, especially during the second field demonstration. The main problem with its use is a lack of predictability. The technique definitely works best when the row is in the direction of highest stratification. This direction can usually be predicted for velocity stratification by examining the local duct geometry. There is no analogous situation for gas sampling, so preliminary survey traversing must be considered a requirement for selection of an optimum gas sampling system. For the data examined during the program, the best Row Average correlation was obtained for the TVA data, since maximum stratification was in the row direction, which was not the case for most of the other data. Recall that this correlation was obtained even though the TVA data had higher stratification levels than did most of the other data.

The recommended procedure for application of the row average technique is as follows:

- Perform a preliminary traverse for the gases of interest at each desired flow condition

- Examine data to determine direction of highest stratification. Couple this with considerations of duct dimensions, access, and other physical constraints to determine the most desirable row direction
- Perform a Row Average analysis of the data to determine the optimum probe location
- Acquire and install sampling hardware
- Perform an in-place system calibration

The row average technique is being recommended for reasons of accuracy and hardware simplicity.

The Walden CO_2 Tracer method is as simple from a hardware standpoint as the Row Average method, but the accuracy does not appear to be as good for the data considered: a uniformly poor correlation was obtained for the ratios of NO_x and SO_2 to CO_2 concentrations. A good correlation may be expected for the SO_2/CO_2 ratio as long as there is little sulfur stratification in the fuel, but such correlation was not observed. The formation of NO_x and CO_2 take place through quite different mechanisms, so we see no obvious reason why the concentration ratio should be constant.

9.3 HARDWARE DEVELOPMENT

Development of gas sampling hardware was not strictly within the scope of the program. Consequently, work in this area was done at a very low level for the sole purpose of providing a way to demonstrate the Row Average technique in the field. The concept behind the probe design is valid for obtaining a representative line average sample. Particulate control was the major problem with the prototype units produced. We feel that validity of the Row Average method has been demonstrated sufficiently to justify serious development of a multi-point linear gas sampling probe for continuous use.

9.4 FIELD DEMONSTRATIONS

A most common problem in field testing is that of obtaining adequate traverse data in a short amount of time. During the field demonstrations,

a 49 point velocity traverse with a pitot-static probe took less than an hour. A full gas sample traverse took eight hours, primarily due to the fact that the gas chromatograph required about five minutes between sample injections. The most common guideline for selection of the number of sampling points is EPA Federal Register Method 1 (Reference 4). On the basis of the data examined, we feel that the number of sample points specified for most situations in Method 1 is overly conservative for gas sampling, and that work should be done to establish a proper minimum number of points for gas sample traverses.

9.5 FINAL COMMENTS

Total mass emissions can be accurately monitored on a continuous basis using hardware and techniques evaluated during the program. We also believe that the proposed Row Average method is acceptable for the continuous monitoring of gas concentration. However, there is no currently available sampling probe hardware for this application. Work should be performed to develop sampling hardware and to properly integrate the flow and sampling subsystems to produce complete real time continuous monitoring systems.

SECTION X
REFERENCES

1. "Continuous Measurement of Total Gas Flowrate from Stationary Sources", EPA-650/2-75-020, Brooks, et al, February, 1975.

2. "Procedures for Measurement in Stratified Gases," EPA-650/2-74-086-a and -b, Zakak, et al, September, 1974.

3. The Analysis of Physical Measurements, E. Pugh and G. Winslow; Addison-Wesley, 1966

4. "Standards of Performance for New Stationary Sources", Environmental Protection Agency; Federal Register, Vol. 36, No. 159, Part II, 9-17-71.

SECTION XI
GLOSSARY

SYMBOL	USAGE	DIMENSIONS
A	area	m^2
c	concentration	$moles/cm^3$
d	diameter	m
$\hat{i},\hat{j},\hat{k}$	unit vectors	dimensionless
$\dot{m}$	mass flow rate	gm/sec
M	molecular weight	$gm/mole$
$\hat{n}$	unit normal vector	dimensionless
n	number	dimensionless
N	number	dimensionless
p	absolute pressure	$torr$
R	universal gas constant	$\frac{gm \cdot m^2}{mole \cdot sec^2 \cdot °K}$
R	gas constant	$\frac{m^2}{sec^2 \cdot °K}$
T	absolute temperature	$°K$
u	axial velocity component	m/sec
$\vec{u}$	total velocity vector	m/sec
$\dot{V}$	volumetric flow rate	m^3/sec
v	velocity	m/sec
μ	mole fraction	dimensionless
ρ	density	gm/cm^3
σ	standard deviation	--
$(\ )_i$	property relative to species i	--
$(\ )_s$	property at standard conditions	--
$\overline{(\ )}$	mean value	--

SECTION XII
APPENDIX

FLOW ANALYSIS PROGRAM

A typical analysis program run is presented. The run shown is the analysis of SO_2 data taken in duct 2 during the 1975 field demonstration. Program development is presented in Section V. Notation shows various features of the program.

```
00100        PROGRAM CONTOUR(INPUT,OUTPUT,TAPE5=INPUT,TAPE7,
00110       1    TAPE6)
00120        REAL LX,LY,KSO2
00130        DIMENSION X1(9),Y1(9),X2(9),Y2(3),IX1(9),IY1(9)
00140       1   ,IX2(9),IY2(9),XX1(25),YY1(25)
00150       2   ,GG1(25,25),GG2(25,25),FX1(25),FY1(25),FF(25)
00160       3   ,ZT1(9,9),ZZ1(69),ZT2(9,3),ZZ2(69)
00170       4   ,FX2(25),FY2(25),FFY(25)
00180       5   ,X1(21),G1C(10),G2C(10),EST(3),SOL(3),SOLR(3),SOLI(3)
00190        COMMON /AU/  B1,B2,B3,GG
00200 C
00210        EQUIVALENCE (ZT1,ZZ1),(ZT2,ZZ2)
00220        NAMELIST /NAM/  LX,LY,A,IM,JM,NC,IG1,NSTOP,IOP,FACTOR
00230       2    ,G1MAX,G2MAX,G1RANGE,G2RANGE,XDIV,IFLAG1,IFLAG2,IFLAG
00240        NAMELIST /NAM1/  ZZ1,ZZ2,X1,Y1,X2,Y2,IX1,IY1,IX2,IY2,KSO2
```

102

```
ZZ1(1)=  6790.,5260.,5608.,5983.,6759.,6433.,6867.,6790.,
         6184.,4903.,4957.,5822.,6070.,5685.,6210.,6184.,
         6255.,4925.,5183.,5763.,6302.,6114.,6134.,6255.,
         6301.,4971.,5480.,5748.,6474.,6423.,6450.,6301.,
         6324.,5037.,5496.,5750.,6565.,6102.,6449.,6324.,
         6473.,5146.,5600.,5862.,6711.,6588.,6748.,6473.,
         6639.,5240.,5663.,6003.,6748.,6624.,6730.,6639.,
         6790.,5260.,5608.,5983.,6759.,6433.,6867.,6790.,
ZZ2(1)=  8.351,7.660,7.108,10.178,9.443,8.087,7.907,8.351,
         1.106,1.428,7.019,7.830,6.96,4.478,4.495,1.106,
         6.783,7.400,5.365,7.942,9.303,8.978,8.693,6.783,
         8.444,8.180,6.262,7.697,7.158,6.760,7.478,8.444,
         5.994,8.480,6.643,8.148,6.763,6.022,6.625,5.934,
         5.749,6.196,6.321,8.857,7.327,6.916,6.782,5.749,
         5.818,7.05,6.722,10.753,8.883,6.513,7.464,5.818,
         8.351,7.660,7.108,10.178,9.443,8.087,7.907,8.351,
KSO2=.05725
```

RAW DATA
INPUT

```
00340        DATA(X1(I),I=1,8) /11.143,.857,2.571,4.286,6.,
00342       1    7.714,9.429,11.143/
00350        DATA(Y1(I),I=1,8) /18.571,1.429,4.286,7.143,10.,12.857,
00352       1    15.714,18.571/
00360        DATA(X2(I),I=1,8) /11.143,.857.2.571,4.286,6.,
00362       1    7.714,9.429,11.143/
00370        DATA(Y2(I),I=1,8) /18.571,1.429,4.286,7.143,10.,12.857,
00372       1    15.714,18.571/
00380        DATA(IX1(I),I=1,7)  /8,0,1,4,1,-1,8/
00390        DATA(IY1(I),I=1,5) /8,1,1,4,1/
00400        DATA(IX2(I),I=1,8)  /8,0,1,4,1,-1,8/
00410        DATA(IY2(I),I=1,5)  /8,1,1,4,1/
00420        LX=12
00430        LY=20
00440        A=240.

00450        IM=25
00460        JM=21
00470        IG1=1
00480        NC=11
00490        XDIV=12.
00500        MAXIT=12
00510        EPSI=1.E-3
00520        G1MAX=230C.
00530        G2MAX=100.
00540        G1RANGE=1000.
00550        G2RANGE=100.
00560        IFLAG1=0
00570        IFLAG2=0
00580        IFLAG=0
00590        FACTOR=.05
00592        IOP=0
00600 C
00610        REWIND 7
00620     5  READ(7,NAM1)
00623        DO 8 I=1,54
```

```
00625      8  ZZ1(I)=KSO2*ZZ1(I)
00630     10  READ(5,NAM)
00640         IF(EOF,5) 20,30
00650     20  GO  TO  40
00660     30  IF(NSTOP .EQ. 0)  GO  TO  50
00670     40  END FILE 6
00680         STOP
00690     50  CONTINUE
00700         WRITE(6,NAM)
00710         IMD=IM-1
00720         JMD=JM-1
00730         HI=LX/IMD
00740         HJ=LY/JMD
00750         L1=IMD/2
00760         M1=(IMD-2)/2
00770         L2=JMD/2
00780         M2=(JMD-2)/2
00790     60  XX1(1)=0.
00800         DO 200 I=2,IM
00810         XX1(I)=XX1(I-1)+HI
00820    200  CONTINUE
00830         YY1(1)=0.

00840         DO 210 I=2,JM
00850         YY1(I)=YY1(I-1)+HJ
00860     90  FORMAT(4X,I5,E12.4)
00870    210  CONTINUE
00880 C
00890         IF(IFLAG1 .EQ. 1)  GO  TO  330
00900         DO 320 J=1,JM
00910         Y=YY1(J)
00920         DO 300 I=1,IM
00930         X=XX1(I)
00940         CALL BVIC(X,Y,Z1,X1,Y1,ZT1,IX1,IY1)
00950         CALL BVIC(X,Y,Z2,X2,Y2,ZT2,IX2,IY2)
00960         Z12=Z1*Z2
```

```
00970         FX1(I)=Z1
00980         FX2(I)=Z2
00990         FF(I)=Z1*Z2
01000         IF(IFLAG .EQ. 0)  GO  TO  300
01010         WRITE(6,77)  I,J,X,Y,Z1,Z2,Z12
01020    300  CONTINUE
01030         CALL  SIMP1(FX2,IM,HI,L1,M1,ANS)
01040         FY2(J)=ANS
01050         CALL SIMP1(FF,IM,HI,L1,M1,ANS)
01060         FFY(J)=ANS
01065         CALL SIMP1(FX1,IM,HI,L1,M1,ANS)
01068         FY1(J)=ANS/12.
01070         WRITE(6,177)  J,FY2(J),FFY(J),FY1(J)
01080    177  FORMAT(2X,*J=*,I5,4X,*INTG2X=*,E12.4,2X,*INTG12X=*,E12.4,
01082        1     2X*INTG1X=*,E12.4)
01090     77  FORMAT(2X,2I5,5E12.4)
01100    320  CONTINUE
01110         CALL  SIMP1(FY2,JM,HJ,L2,M2,A2)
01120         CALL  SIMP1(FFY,JM,HJ,L2,M2,A12)
01125         CALL  SIMP1(FY1,JM,HJ,L2,M2,A1)
01127         GB1=A1/20.
01130         GB2=A2/A
01140         GB12=A12/A2
01150         WRITE(6,47)  A2,A12,GB2,GB12,GB1
01160     47  FORMAT(//2X,*A2=*,E14.6,3X,*A12=*,E14.6/
01170        1    2X,*G2BAR=*,E14.6,5X,*G12BAR=*,E14.6,5X,*G1BAR=*,E14.6//)
01172 C
01180   330   IF(G14AX  .EQ. 0)  GO  TO  10
01190         ID=XDIV+1

01200         HXM=LX/XDIV
01210         XM(1)=0.
01220         DO  340  I=2,ID
01230         XM(I)=XM(I-1)+HXM
01240    340  CONTINUE
01250         IF(IOP .EQ. 0)  GO  TO  360
```

```
01260         DO  350 I=1,NC
01270         G1C(I)=G1MAX-I*G1RANGE/NC
01280         G2C(I)=G2MAX-I*G2RANGE/NC
01290    350  CONTINUE
01300         GO  TO  380
01302 C
01310    360  DIF1=FACTOR*GB12
01320         DIF2=FACTOR*GB2
01330         G1C(1)=GB12-(NC-1)/2 *DIF1
01340         G2C(1)=GB2-(NC-1)/2 * DIF2
01350         DO  370  I=2,NC
01360         G1C(I)=G1C(I-1)+DIF1
01370         G2C(I)=G2C(I-1)+DIF2
01380    370  CONTINUE
01390    380  JJ=JMD
01400         DO  500  IX=1,ID
01410         X=XM(IX)
01420         DO  500  IY=1,JM
01430         Y=YY1(IY)
01440         CALL  BVIC(X,Y,Z1,X1,Y1,ZT1,IX1,IY1)
01450         IF(Z1 .LT. 0)  Z1=0.
01460         GG1(IY,IX)=Z1
01470         CALL  BVIC(X,Y,Z2,X2,Y2,ZT2,IX2,IY2)
01480         IF(Z2 .LT. 0)  Z2=0.
01490         GG2(IY,IX)=Z2
01500    500  CONTINUE
01502 C
01510         DO 510  IG=IG1,2
01520         GO  TO  (460,470) IG
01530    460  WRITE(6,1020)
01540   1020  FORMAT(/6X,*Y*,10X,*SP*,9X,*Y*,10X,*SP*,
01550        1   9X,*Y*,10X,*SP*/)
01560         GO  TO  480
01570    470  WRITE(6,1030)
01580   1030  FORMAT(/6X,*Y*,9X,*VEL*,9X,*Y*,9X,*VEL*,
01590        1   9X,*Y*,9X,*VEL*/)
```

```
01600    480 DO  490  IX=1,ID
01610        X=XM(IX)
01620        WRITE(6,1040)  X
01630   1040 FORMAT(2X,*X=*,F5.2)
01640        IF(IG .NE.1)  GO  TO  485
01650        WRITE(6,1050)  (YY1(IY),GG1(IY,IX) ,IY=1,JM)
01660   1050 FORMAT(2X,3(E10.2,E12.4))
01670        GO  TO  490
01680    485 WRITE(6,1050)  (YY1(IY),GG2(IY,IX) ,IY=1,JM)
01690    490 CONTINUE
01700    510 CONTINUE
01710 C
01720        DO  800 IG=IG1,2
01730        WRITE(6,277)
01740    277 FORMAT(///)
01750        DO  800  I=1,NC
01760        IF(IG .NE. 1)  GO  TO  520
01770        GG=G1C(I)
01780        GO  TO  540
01790    520 GG=G2C(I)
01800    540 DO  740  J=1,ID
01810        X=XM(J)
01820        DO  610  IJ=1,JM
01830        Y=YY1(IJ)
01840        IF(IG .NE. 1)  GO  TO  560
01850        FX1(IJ)=GG1(IJ,J)
01860        GO  TO  610
01870    560 FX1(IJ)=GG2(IJ,J)
01880    610 CONTINUE
01890    620 DO  720  K=1,JJ
01900        KN=2
01910        YLEFT=YY1(K)
01920        YRIGHT=YY1(K+1)
01930        IF(GG .LE. FX1(K) .AND. GG .GE. FX1(K+1)) GO TO 710
01940        IF(GG .GE. FX1(K) .AND. GG .LE. FX1(K+1)) GO TO 710
```

```
01950         GO  TO  720
01960    710  ZD1=FX1(K+1)-FX1(K)
01970         YD2=YY1(K+1)-YY1(K)
01980         YY=(GG-FX1(K))*YD2/ZD1+YY1(K)
01990         IF(IG .EQ. 2)  GO  TO  715
02000         WRITE(6,1000)  IG,I,K,GG,X,YY
02010         GO  TO  720

02020    715  WRITE(6,1010) IG,I,K,GG,X,YY
02030   1010  FORMAT(2X,*IG=*,I2,2X,*I=*,I3,2X,*K=*,I2,2X,
02040        1   *VEL=*,F6.1,2X,*X=*,F4.1,2X,*Y=*,F5.2)
02050   1000  FORMAT(2X,*IG=*,I2,2X,*I=*,I3,2X,*K=*,I2,2X,
02060        1   *SP=*,F6.1,2X,*X=*,F4.1,2X,*Y=*,F5.2)
02070    720  CONTINUE
02080         WRITE(6,975) K,X
02090    975  FORMAT(2X,*K=*,I2,2X,*X=*,F5.1)
02100    740  CONTINUE
02110         WRITE(6,980) J,X
02120    980  FORMAT(2X,*J=*,I3,2X,*X=*,F5.1)
02130    800  CONTINUE
02140         GO  TO  10
02150         END
02160 C
02200         SUBROUTINE SIMP1(Y,N,DEL,L,M,ANS)
02210         DIMENSION Y(1)
02220         SUM1=0
02230         DO  2  I=1,L
02240         I1=2*I
02250      2  SUM1=SUM1+Y(I1)
02260         SUM2=0
02270         IF(M)  5,5,3
02280      3  DO  4  J=1,M
02290         I2=2*J+1
02300      4  SUM2=SUM2+Y(I2)
02310      5  ANS=.333333333333*DEL*(Y(1)+Y(N)+4.*SUM1+2.*SUM2)
02320         RETURN
02330         END
```

CONSTANTS

```
$NAM
LX       = 1.2E+01,
LY       = 2.0E+01,
A        = 2.4E+02,
IM       = 25,
JM       = 21,
NC       = 11,
IG1      = 1,
NSTOP    = 0,
IOP      = 0,
FACTOR   = 5.0E-02,
G1MAX    = 2.3E+03,
G2MAX    = 1.0E+02,
G1RANGE  = 1.0E+03,
G2RANGE  = 1.0E+02,
XDIV     = 1.2E+01,
IFLAG1   = 0,
IFLAG2   = 0,
IFLAG    = 0,
$END
```

		VELOCITY		FLOW PROPORTIONAL AVE.		SPATIAL AVE.	
J=	1	INTG2X=	8.7929E+01	INTG12X=	2.4306E+04	INTG1X=	2.8139E+02
J=	2	INTG2X=	8.0849E+01	INTG12X=	2.3247E+04	INTG1X=	2.8744E+02
J=	3	INTG2X=	7.6854E+01	INTG12X=	2.2711E+04	INTG1X=	2.9395E+02
J=	4	INTG2X=	7.5942E+01	INTG12X=	2.2937E+04	INTG1X=	3.0092E+02
J=	5	INTG2X=	7.8115E+01	INTG12X=	2.4112E+04	INTG1X=	3.0836E+02
J=	6	INTG2X=	8.4794E+01	INTG12X=	2.6816E+04	INTG1X=	3.1601E+02
J=	7	INTG2X=	9.6083E+01	INTG12X=	3.1180E+04	INTG1X=	3.2386E+02
J=	8	INTG2X=	1.0451E+02	INTG12X=	3.4894E+04	INTG1X=	3.3320E+02
J=	9	INTG2X=	1.0483E+02	INTG12X=	3.6439E+04	INTG1X=	3.4683E+02
J=	10	INTG2X=	1.0038E+02	INTG12X=	3.6514E+04	INTG1X=	3.6295E+02
J=	11	INTG2X=	9.5234E+01	INTG12X=	3.5608E+04	INTG1X=	3.7308E+02
J=	12	INTG2X=	9.0006E+01	INTG12X=	3.3498E+04	INTG1X=	3.7099E+02
J=	13	INTG2X=	8.4400E+01	INTG12X=	3.0790E+04	INTG1X=	3.6301E+02
J=	14	INTG2X=	8.1104E+01	INTG12X=	2.9323E+04	INTG1X=	3.5939E+02
J=	15	INTG2X=	8.1941E+01	INTG12X=	2.9958E+04	INTG1X=	3.6393E+02
J=	16	INTG2X=	8.4051E+01	INTG12X=	3.1240E+04	INTG1X=	3.7073E+02
J=	17	INTG2X=	8.3560E+01	INTG12X=	3.1304E+04	INTG1X=	3.7386E+02
J=	18	INTG2X=	8.0522E+01	INTG12X=	3.0156E+04	INTG1X=	3.7342E+02
J=	19	INTG2X=	7.5579E+01	INTG12X=	2.8177E+04	INTG1X=	3.7053E+02
J=	20	INTG2X=	6.9018E+01	INTG12X=	2.5417E+04	INTG1X=	3.6518E+02
J=	21	INTG2X=	6.0551E+01	INTG12X=	2.1950E+04	INTG1X=	3.5738E+02

ROW AVERAGES

A2= 1.7J2184E+J1 A12= 5.876611E+05

G2BAR= 7.092432E+00 G12BAR= 3.452395E+02 G1BAR= 3.439082E+02

MEAN VALUES

Y	SP	Y	SP	Y	SP
X= 0.00					
0.	3.0353E+02	1.00E+00	2.8592E+02	2.00E+00	2.7553E+02
3.00E+00	2.7234E+02	4.00E+00	2.7636E+02	5.00E+00	2.9023E+02
6.00E+00	3.1412E+02	7.00E+00	3.3422E+02	8.00E+00	3.4199E+02
9.00E+00	3.4284E+02	1.00E+01	3.3958E+02	1.10E+01	3.2865E+02
1.20E+01	3.1443E+02	1.30E+01	3.1143E+02	1.40E+01	3.2828E+02
1.50E+01	3.5147E+02	1.60E+01	3.6355E+02	1.70E+01	3.6477E+02
1.80E+01	3.5846E+02	1.90E+01	3.4459E+02	2.00E+01	3.2319E+02
X= 1.00					
0.	2.9537E+02	1.00E+00	2.8398E+02	2.00E+00	2.7800E+02
3.00E+00	2.7745E+02	4.00E+00	2.8232E+02	5.00E+00	2.9441E+02
6.00E+00	3.1385E+02	7.00E+00	3.3120E+02	8.00E+00	3.4122E+02
9.00E+00	3.4722E+02	1.00E+01	3.4875E+02	1.10E+01	3.4221E+02
1.20E+01	3.3170E+02	1.30E+01	3.2808E+02	1.40E+01	3.3647E+02
1.50E+01	3.4889E+02	1.60E+01	3.5605E+02	1.70E+01	3.5806E+02
1.80E+01	3.5671E+02	1.90E+01	3.5198E+02	2.00E+01	3.4390E+02
X= 2.00					
0.	2.8658E+02	1.00E+00	2.8223E+02	2.00E+00	2.8124E+02
3.00E+00	2.8371E+02	4.00E+00	2.8864E+02	5.00E+00	2.9998E+02
6.00E+00	3.1482E+02	7.00E+00	3.2809E+02	8.00E+00	3.4077E+02
9.00E+00	3.5113E+02	1.00E+01	3.5675E+02	1.10E+01	3.5378E+02
1.20E+01	3.4630E+02	1.30E+01	3.4259E+02	1.40E+01	3.4539E+02
1.50E+01	3.5044E+02	1.60E+01	3.5386E+02	1.70E+01	3.5571E+02
1.80E+01	3.5671E+02	1.90E+01	3.5687E+02	2.00E+01	3.5619E+02
X= 3.00					
0.	2.7690E+02	1.00E+00	2.8055E+02	2.00E+00	2.8542E+02
3.00E+00	2.9149E+02	4.00E+00	2.9877E+02	5.00E+00	3.0736E+02
6.00E+00	3.1726E+02	7.00E+00	3.2795E+02	8.00E+00	3.4065E+02
9.00E+00	3.5455E+02	1.00E+01	3.6360E+02	1.10E+01	3.6358E+02
1.20E+01	3.5875E+02	1.30E+01	3.5565E+02	1.40E+01	3.5581E+02
1.50E+01	3.5689E+02	1.60E+01	3.5758E+02	1.70E+01	3.5818E+02
1.80E+01	3.5865E+02	1.90E+01	3.5906E+02	2.00E+01	3.5943E+02

EXPANDED MATRIX CONCENTRATION DATA

(CONTINUES)

Y	VEL	Y	VEL	Y	VEL
X= 0.00					
0.	0.	1.00E+00	0.	2.00E+00	3.1954E-02
3.00E+00	4.9234E+00	4.00E+00	8.1768E+00	5.00E+00	9.5144E+00
6.00E+00	8.9230E+00	7.00E+00	7.7681E+00	8.00E+00	6.7795E+00
9.00E+00	5.4959E+00	1.00E+01	4.0990E+00	1.10E+01	2.4245E+00
1.20E+01	6.8234E-01	1.30E+01	0.	1.40E+01	0.
1.50E+01	3.8426E-01	1.60E+01	1.9805E-01	1.70E+01	0.
1.80E+01	0.	1.90E+01	0.	2.00E+01	0.
X= 1.00					
0.	0.	1.00E+00	1.1152E+00	2.00E+00	3.3428E+00
3.00E+00	5.1307E+00	4.00E+00	6.4788E+00	5.00E+00	7.3405E+00
6.00E+00	7.7122E+00	7.00E+00	7.8397E+00	8.00E+00	7.8660E+00
9.00E+00	7.7004E+00	1.00E+01	7.3279E+00	1.10E+01	6.5908E+00
1.20E+01	5.6700E+00	1.30E+01	5.0624E+00	1.40E+01	5.0880E+00
1.50E+01	5.2453E+00	1.60E+01	4.8668E+00	1.70E+01	3.8617E+00
1.80E+01	2.6572E+00	1.90E+01	9.5323E-01	2.00E+01	0.
X= 2.00					
0.	7.1645E+00	1.00E+00	6.2705E+00	2.00E+00	5.7031E+00
3.00E+00	5.4624E+00	4.00E+00	5.5482E+00	5.00E+00	6.0519E+00
6.00E+00	6.9801E+00	7.00E+00	7.8532E+00	8.00E+00	8.4185E+00
9.00E+00	8.8356E+00	1.00E+01	9.0260E+00	1.10E+01	8.8660E+00
1.20E+01	8.4837E+00	1.30E+01	8.2003E+00	1.40E+01	8.1660E+00
1.50E+01	8.1234E+00	1.60E+01	7.7398E+00	1.70E+01	7.0200E+00
1.80E+01	6.0272E+00	1.90E+01	4.7614E+00	2.00E+01	3.2225E+00
X= 3.00					
0.	1.1130E+01	1.00E+00	8.7881E+00	2.00E+00	7.0610E+00
3.00E+00	5.9487E+00	4.00E+00	5.4511E+00	5.00E+00	5.7165E+00
6.00E+00	6.7557E+00	7.00E+00	7.7896E+00	8.00E+00	8.3751E+00
9.00E+00	8.7928E+00	1.00E+01	9.0462E+00	1.10E+01	9.0773E+00
1.20E+01	8.9527E+00	1.30E+01	8.8556E+00	1.40E+01	8.8673E+00
1.50E+01	8.8607E+00	1.60E+01	8.6919E+00	1.70E+01	8.3629E+00
1.80E+01	7.9010E+00	1.90E+01	7.3064E+00	2.00E+01	6.5789E+00

EXPANDED MATRIX VELOCITY DATA

(CONTINUES)

```
IG= 1  I=  6  K=15  SP= 345.2  X=  0.0  Y=14.73
IG= 1  I=  6  K=19  SP= 345.2  X=  0.0  Y=18.95
K=20  X=  0.0
IG= 1  I=  6  K= 9  SP= 345.2  X=  1.0  Y= 8.67
IG= 1  I=  6  K=11  SP= 345.2  X=  1.0  Y=10.54
IG= 1  I=  6  K=15  SP= 345.2  X=  1.0  Y=14.71
IG= 1  I=  6  K=20  SP= 345.2  X=  1.0  Y=19.83
K=20  X=  1.0
IG= 1  I=  6  K= 9  SP= 345.2  X=  2.0  Y= 8.43
IG= 1  I=  6  K=13  SP= 345.2  X=  2.0  Y=12.28
IG= 1  I=  6  K=14  SP= 345.2  X=  2.0  Y=13.95
K=20  X=  2.0
IG= 1  I=  6  K= 9  SP= 345.2  X=  3.0  Y= 8.33
K=20  X=  3.0
IG= 1  I=  6  K= 9  SP= 345.2  X=  4.0  Y= 8.26
K=20  X=  4.0
IG= 1  I=  6  K= 9  SP= 345.2  X=  5.0  Y= 8.19
K=20  X=  5.0
IG= 1  I=  6  K= 9  SP= 345.2  X=  6.0  Y= 8.10
K=20  X=  6.0
IG= 1  I=  6  K= 8  SP= 345.2  X=  7.0  Y= 7.91
K=20  X=  7.0
IG= 1  I=  6  K= 8  SP= 345.2  X=  8.0  Y= 7.64
K=20  X=  8.0
IG= 1  I=  6  K= 8  SP= 345.2  X=  9.0  Y= 7.31
K=20  X=  9.0
IG= 1  I=  6  K= 8  SP= 345.2  X= 10.0  Y= 7.17
K=20  X= 10.0
IG= 1  I=  6  K= 8  SP= 345.2  X= 11.0  Y= 7.26
K=20  X= 11.0
IG= 1  I=  6  K= 8  SP= 345.2  X= 12.0  Y= 7.51
K=20  X= 12.0
```

LOCUS OF MEAN CONCENTRATION PROFILES

(CONTINUES FOR OTHER CONCENTRATIONS)

```
IG= 2  I=  6  K= 4  VEL=   7.1  X= 0.0  Y= 3.67
IG= 2  I=  6  K= 8  VEL=   7.1  X= 0.0  Y= 7.68
K=20   X=  0.0
IG= 2  I=  6  K= 5  VEL=   7.1  X= 1.0  Y= 4.71
IG= 2  I=  6  K=11  VEL=   7.1  X= 1.0  Y=10.32
K=20   X=  1.0
IG= 2  I=  6  K= 1  VEL=   7.1  X= 2.0  Y=  .08
IG= 2  I=  6  K= 7  VEL=   7.1  X= 2.0  Y= 6.13
IG= 2  I=  6  K=17  VEL=   7.1  X= 2.0  Y=15.90
K=20   X=  2.0
IG= 2  I=  6  K= 2  VEL=   7.1  X= 3.0  Y= 1.98
IG= 2  I=  6  K= 7  VEL=   7.1  X= 3.0  Y= 6.33
IG= 2  I=  6  K=20  VEL=   7.1  X= 3.0  Y=19.29
K=20   X=  3.0
IG= 2  I=  6  K= 3  VEL=   7.1  X= 4.0  Y= 2.41
IG= 2  I=  6  K= 7  VEL=   7.1  X= 4.0  Y= 6.11
K=20   X=  4.0
IG= 2  I=  6  K= 3  VEL=   7.1  X= 5.0  Y= 2.83
IG= 2  I=  6  K= 6  VEL=   7.1  X= 5.0  Y= 5.71
IG= 2  I=  6  K=10  VEL=   7.1  X= 5.0  Y= 9.34
IG= 2  I=  6  K=16  VEL=   7.1  X= 5.0  Y=15.93
K=20   X=  5.0
```

LOCUS OF MEAN VELOCITY PROFILES

(CONTINUES FOR OTHER PROFILES)